EVALUATION AND ANALYSIS OF ARRAY ANTENNAS FOR PASSIVE COHERENT LOCATION (PCL) SYSTEMS

THESIS

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Abstract
Passive Coherent Location (PCL) systems use a special form of a radar receiver that exploits the ambient radiation in the environment to detect and track targets. Typical transmissions of opportunity that might be exploited include television and FM radiobroadcasts. PCL implies the use of a non-radar electromagnetic sources of illumination, such as commercial radio or television broadcasts also referred as transmitters of opportunity. The use of such illumination sources means that the receiver needs to process waveforms that are not designed for radar purposes. As a consequence, the receivers for PCL sysems must be much more customized than traditional receivers, in order to obtain the most appropriate and best signal. Since antennas are the eyes of the receivers, processing of an incoming signal starts with the antennas. Yet, because PCL system is non-traditional, there has not been much work done in the evaluation of the antennas, even though PCL systems have some demanding constraints on the antenna system. During this research various array antenna designs will be studied by their radiation patterns, gain factors, input impedances, power efficiencies and other features by simulating these arrays in the computer environment. The goal is to show the better performance of the array antennas compared to traditional Yagi-Uda antennas that are currently used for PCL systems.

Subject Terms
Passive Radar, Passive Coherent Location System, Passive Sensor Location System, Bistatic radar Multistaic Radar, Yagi-Uda Antennas, Array Antennas, Direction of Arrival

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Table of Contents

List of Figures

List of Tables

Acronym List

Abbreviation	Acronym
ACMA	Analytical Constant Modulus Algorithm
AF	Array Factor
AFIT	Air Force Institute of Technology
AGARD	Advisory Group for Aerospace Research and Development
AM	Amplitude Modulation
AMP	Antenna Modeling Program
ARM	Anti Radiation Missile
AWG	American Wire Gauge
BALUN	Balanced to Unbalanced
CBF	Conventional Beam Forming
CW	Continuous Wave
DOA	Directional Of Arrival
ECCM	Electronic Counter Counter Measures
ECM	Electronic Counter Measures
ESM	Electronic Support Measures
FEBA	Forward Edge of Battle Area
FM	Frequency Modulation
GA	Genetic Algorithm
HARM	High-speed Anti Radiation Missile
IF	Intermediate Frequency
LOS	Line of Sight
MUSIC	Multiple Signal Characterization
MTI	Moving Target Indicator
NEC	Numerical Electromagnetics Code
RADAR	Radio Detection And Range
RCS	Radar Cross Section
RF	Radio Frequency
RMS	Root-Mean-Square
SLL	Sidelobe Level
SNR	Signal to Noise Ratio
TuAF	Turkish Air Force
TV	Television
UHF	Ultra High Frequency
VHF	Very High Frequency
VLF	Very Low Frequency
VSWR	Voltage Standing Wave Ratio
USAF	United States Air Force

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Abstract

Passive Coherent Location (PCL) systems use a special form of a radar receiver that exploits the ambient radiation in the environment to detect and track targets. Typical transmissions of opportunity that might be exploited include television and FM radiobroadcasts. PCL implies the use of a non-radar electromagnetic sources of illumination, such as commercial radio or television broadcasts, also referred as transmitters of opportunity. The use of such illumination sources means that the receiver needs to process waveforms that are not designed for radar purposes. As a consequence, the receivers for PCL systems must be much more customized than traditional receivers, in order to obtain the most appropriate and best signal.

Since antennas are the *eyes* of the receivers, processing of an incoming signal starts with the antennas. Yet, because PCL system is non-traditional, there has not been much work done in the evaluation of the antennas, even though PCL systems have some demanding constraints on the antenna system. During this research various array antenna designs will be studied by their radiation patterns, gain factors, input impedances, power efficiencies, and other features by simulating these arrays in the computer environment. The goal is to show the better performance of the array antennas compared to traditional Yagi-Uda antennas that are currently used for PCL systems.

Evaluation and Analysis of Array Antennas for Passive Coherent Location Systems

Chapter 1 - INTRODUCTION

1.1 Background

We can say that the antennas are the *eyes* of the receivers, and the processing of an incoming signal starts with the antennas. Yet, because Passive Coherent Location (PCL) systems are non-traditional and new, therefore not been much work has been done in the analysis of antennas that are used for these systems. Instead, since the PCL systems depend primarily on software, PCL designers mainly work on the receiver part of the system. However, array antenna designs are possible structures that can improve the effectiveness of a PCL system.

There are two fundamental parameters related to an antenna design: coverage and angular resolution. These two parameters are directly concerned with the effectiveness of any receiver system.

First, to understand the effect of an antenna on PCL receiver coverage, it would be appropriate to look at the bistatic radar range equation since the PCL

system is a bistatic case. The radar range equation for a bistatic case according to [1] is as follows:

$$(R_T R_R)_{max} = \left[\frac{P_T G_T G_R \lambda^2 \sigma_B F_T F_R}{(4\pi)^3 k T_S B_n (S/N)_{min} L_T L_R} \right]^{1/2} = \kappa \qquad (1)$$

where, R_T = transmitter-to-target range,

R_R = receiver-to-target range,

P_T = transmitter power output,

G_T = transmitting antenna power gain,

G_R = receiving antenna power gain,

λ = wavelength,

σ_B = bistatic radar target cross section,

F_T = pattern propagation factor for transmitter-to-target path,

F_R = pattern propagation factor for receiver-to-target path,

k = Boltzmann's constant,

T_S = receiving system noise temperature

B_n = noise bandwidth of receiver's predetection filter, sufficient to pass all spectral components of the transmitted signal,

$(S/N)_{min}$= signal-to-noise power ratio required for detection,

L_T = transmitting system loss (>1) not included in other parameters,

L_R = receiving system loss (>1) not included in other parameters,

κ = bistatic maximum range product.

This equation tells us that the receiver antenna gain is proportional to the square of range which defines the coverage. In the conventional radar case, this dependency is twice that of a bistatic case and according to [2]. Because of this dependency, the receiver antenna gain is considered essential for a better bistatic radar coverage area.

Another aspect for a PCL case is the received power that can be derived as,

$$P_R = P_T + P_{L1} + G_T + P_{L2} + G_R \qquad (2)$$

where, P_R = Received power,

P_T = Transmitter power,

P_{L1} = Path loss (transmitter to target),

G_T = Gain of target,

P_{L2} = Path loss (target to receiver),

G_R = Gain of the receiver,

In this equation, the only parameter we can control is the gain of the receiver, which is basically the antenna gain. Increasing the gain of the antenna will automatically increase the received power, which will increase the range of the PCL system respectively.

Second, angular resolution is another important parameter for a radar receiver, and, of course, for a PCL system. Resolution, which is "the ability to recognize closely spaced objects" [2] is directly related to the electrical size of an antenna. In other words, the bigger the electrical size, the better the resolution

of that antenna. "The size of the radar antenna measured in wavelengths is inversely proportional to its beamwidth and hence determines the radar's angular resolution" [2].

1.2 Problem

For a radar receiver to be more effective, engineers need to increase their knowledge of these two antenna parameters, i.e. coverage and resolution. However, PCL receiver systems are a new concept and the engineers were more interested in signal processing rather than antenna design. They used traditional Yagi antennas, which are generally used for a television broadcast reception, since PCL systems exploit commercial TV or FM broadcasts. Using more elements in an *array antenna* design, will increase the gain and will narrow the main beam, which will help to better these two basic parameters for a PCL system receiver.

In PCL systems, Directional Of Arrival (DOA) estimation in azimuth has always been the first focus for the engineers. DOA estimation is done by different techniques, such as Conventional Beam Forming (CBF), Multiple Signal Characterization (MUSIC) or Analytical Constant Modulus Algorithm (ACMA). For these DOA estimation techniques, interferometry is the common method to acquire the incoming signal. Since interferometry mainly depends on the difference of an incoming signal data among the channels of a receiver, that receiver should have at least two channels. By using an array antenna, the

number of the receiver channels will be increased and this will provide more accurate DOA results.

Moreover, increasing the number of the elements in the antenna design will cause an increase of the electrical size of the antenna. This will cause the main beam to become narrower since the angular resolution depends on the aperture size of an antenna.

Besides, using an array antenna design in a PCL receiver system configuration will allow engineers to take advantage of the new DOA estimation techniques such as MUSIC or ACMA for PCL systems.

In addition, using an array antenna will aid in making use of some array antenna attributes such as sidelobe reduction techniques, super directivity, etc., which will result in a better performance within the PCL system.

Furthermore, the increased number of channels will acquire more information and data about the received signal, which will certainly improve the precision within the receiver system.

All in all, there is a crucial need for analysis of the array antenna designs and structures for a possible PCL receiver system. An array antenna application in the PCL configuration will enhance the reliability and accuracy of a PCL system.

1.3 Summary of Current Knowledge

1.3.1 Antenna Basics and Parameters

An antenna is any device which converts electronic signals (i.e. signals in cables) to electromagnetic waves – or vice versa. Figure 1 shows the fundamental parameters of an antenna to clarify its features.

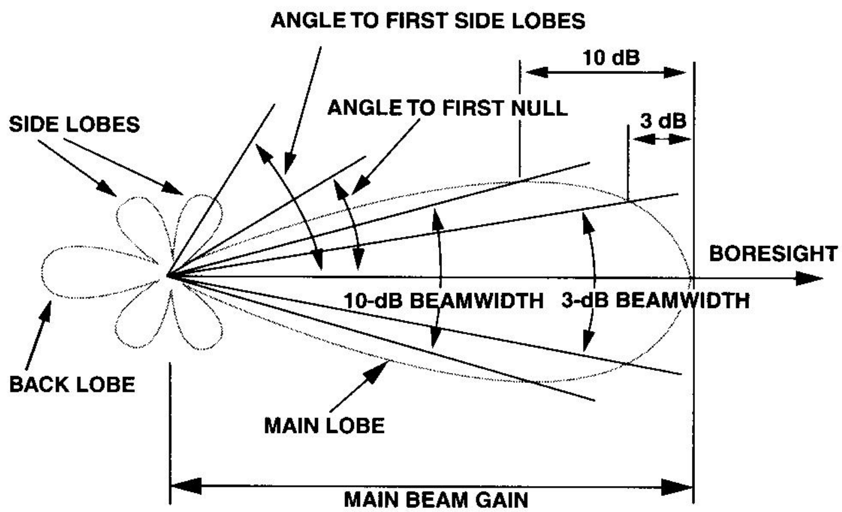

Figure 1: Geometry of the Antenna Pattern

According to [3] the fundamental parameters of an antenna as follows:

Boresight: The direction that the antenna is designed to point.

Main Lobe: The primary or maximum beam of the antenna.

Beamwidth: The width of the beam (in degrees and usually refers to the 3-dB beamwidth) that denotes the angular coverage of the antenna.

3-dB Beamwidth: The two-sided angle between the angles at which the antenna gain is reduced to half of the gain at the boresight (i.e., 3-dB gain reduction).

Sidelobes: Antennas have other than intended (main beam) beams as shown in the figure. The back lobe is the opposite direction from the main beam, and the sidelobes are at other angles.

Angle to the first sidelobe: The angle from the boresight of the main beam to the maximum gain direction of the first sidelobe.

Angle to the first null: The angle from the boresight to the minimum gain point between the main beam and the first sidelobe.

Gain: The increase in the signal strength (commonly stated in dB) as the signal is processed by the antenna.

Frequency coverage: The frequency range over which the antenna can transmit or receive signals and provide the appropriate parametric performance.

Bandwidth: The frequency range of the antenna in units of frequency.

Polarization: The orientation of the Electric (*E*) or Magnetic (*H*) fields as transmitted or received.

Radiation intensity: The power radiated from an antenna per unit solid angle.

Directivity: The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions.

1.3.2 PCL Receiver Antenna Designs

1.3.2.1 Yagi Uda Antennas

Yagi-Uda Antenna is a combination of a single driven antenna and closely coupled parasitic elements, which may function either as a reflector as a result of inductive reactance, or as a director as a result of capacitance reactance, depending on both the length and spacing of the parasitic element; also called Yagi antenna. Such structures are not only feasible but have a rather important place in antenna practice and concept, particularly in Very High Frequency (VHF) and Ultra High-Frequency (UHF) ranges. Because Yagi Uda antennas are not only inexpensive, but also very convenient for reception of TV and FM broadcasts, they became as the most commonly used antennas by the PCL system designers. The basic shape and characteristics of a typical Yagi Uda antenna is shown in Figure 2.

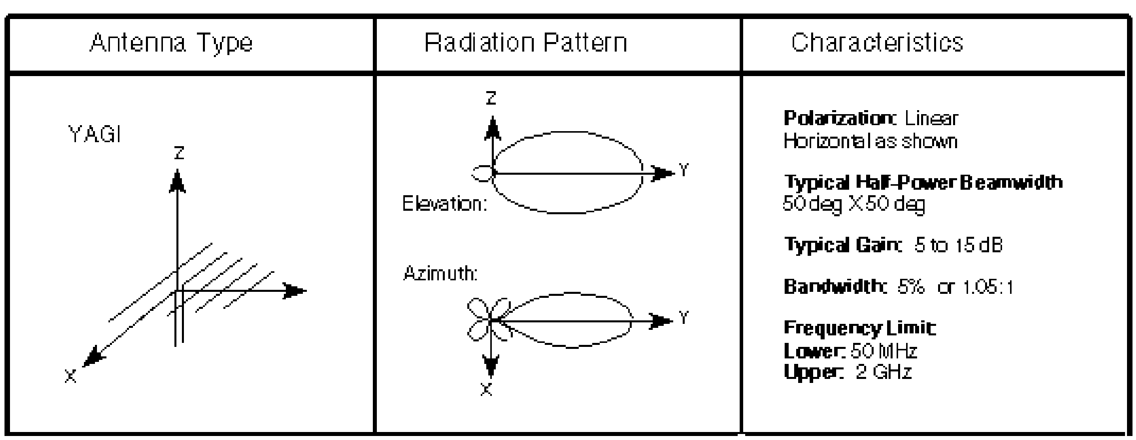

Figure 2: Typical Yagi Uda Antenna

1.3.2.2 Array Antennas

"In many applications it is necessary to design antennas with very high gains to meet the demands of long distance communication. This can only be accomplished by increasing the electrical size of the antenna" [4]. Using more than one element within the antenna is a way of enlarging the antenna dimensions without increasing the individual elements. This type of an antenna is called an *array antenna*. Generally, for mathematical convenience, elements are chosen identical to each other since it simplifies the practical usage and computation. Basic shape and characteristic of an array antenna is shown in Figure 3.

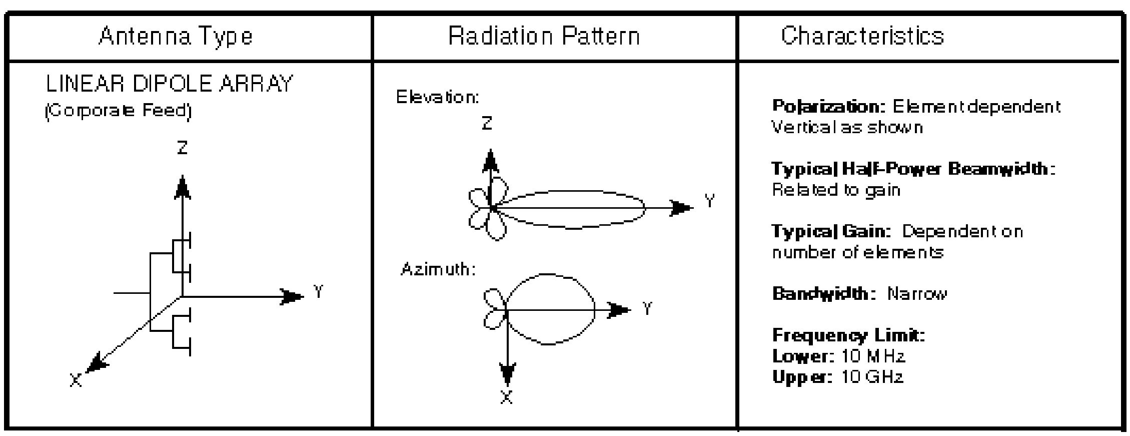

Figure 3: Typical 2-Element Linear Array Antenna

An antenna array is a group of antennas arranged in such a way to produce a radiated field with specific radiation characteristics which cannot be achieved by a single antenna. There are several different configurations used for grouping individual antennas into arrays. The most common array configurations are linear

(uniform, non-uniform, binomial, etc.), two-dimensional (circular, rectangular, etc.), and three-dimensional (cubic, spherical, etc.).

1.3.2.3 Phased Arrays

Basically, the phased array antenna is an array antenna, which is compromised of a group of individual radiators that are distributed and oriented in a one-dimensional or two-dimensional spatial configuration. "The amplitude and phase excitations of each radiator can be individually controlled to form a radiated beam of any desired shape (directive pencil beam or fan beam shape) in space" [2].

1.3.3 Current PCL Receiver Antennas

There are at least four PCL systems that are known to operate successfully: Griffiths' TV Based Bistatic Radar [5], Lodwig's Silent Sentry II [6], Howland's TV Based Bistatic Radar [7], and Saar's Manastash Ridge Radar [8]. With the exception of the Silent Sentry II system, the other three systems use a Yagi antenna as a receiver antenna. The Silent Sentry II system uses a linear phased array antenna to receive the signals in the environment.

The first application of a PCL system was introduced by Griffiths and his colleagues in 1985, which is known as *Television-based Bistatic Radar I*. "A 10 element Yagi, mounted on the roof of a building and directed at the TV transmitter, was used to provide the reference signal. A vertical array of four 17-

element Yagis was used for most of the echo reception. This antenna was mounted on the side of a building to provide some shielding from the direct signal. This array was spaced to direct its first null at 15°-elevation and tilted upwards by this angle to reduce ground clutter problems. The gain over isotropic of this system was calculated as 17 dB. The total level of signal (i.e. direct + clutter) received from it is –32 to –35 dBm (vision carrier). At a later stage, a single Yagi on a rotator was used some experiments" [5].

"A horizontal linear phased array antenna is used in the current Silent Sentry 2 (SS2) implementation. Target array is a linear phased array for detecting the scattered energy from targets in the region of interest. Moreover, reference antennas are single elements which are identical to those in the target array, and are used for reception of the direct path from the FM illuminators" [6]. "Furthermore, SS2 target array antenna is a 9m x 2.4m wall-mounted array where its elements are *cavities*. Reference antennas are generally built on top of a vehicle or a building" [9].

"In Howland's PCL system, object bearing is performed using phase interferometry, with a pair of eight element Yagi-Uda antennas, horizontally spaced about 0.6 wavelengths apart, giving an unambiguous measurement range of approximately ±56° about boresight. As the system operates in the Very High Frequency (VHF) and Ultra High Frequency (UHF) bands, multipath propagation is a potential cause of reduced low-level coverage. To overcome this, the antennas are mounted on an 18 meters high mobile tower, 33

wavelengths above the ground, giving low-level coverage comparable to S-band radar 3 meters above the ground. Each Yagi-Uda antenna has a dedicated processing channel, which down-converts the received signal to HF in a two-stage process, using intermediate frequencies of 290 MHz and 29 MHz" [7].

The Manastash Ridge Radar, which was designed by John Sahr, uses a single channel Yagi antenna within the receiver. The receiver antenna consists of 8 elements and is separated from the transmitter antenna by 100 km.

1.4 Scope

In this thesis research, array antenna designs are analyzed and are evaluated for PCL systems with regard to DOA estimation in azimuth. Different element configurations and spacings, and the various excitation phases and amplitudes of the individual elements will be examined in a typical linear array antenna designs. The effect of changing variables- such as length and the diameter of the elements, element materials, different element shapes, different media, etc.- while designing a linear array antenna will be studied thoroughly.

1.5 Approach / Methodology

A PCL system has some quite demanding constraints on the antenna design compared with other systems. Some typical desirable features are:

√*Broadband* - i.e. we want this antenna to exploit FM frequency emissions that are from 88MHz to 108MHz,

√ *High Gain* – since the peak power of a PCL system is noticeably low compared to typical radar peak power, we need the PCL antenna have higher gain to overcome this handicap,

√*Good Directionality,*

√*Low Sidelobes*,

√*Low cost* – since one of the most important features of a PCL system is its low cost, designers usually prefer to build a cheap antenna within the receiver system.

For the antenna array, and for the structure as a whole it should be:

√ *Able to steer nulls at jammers, interferers, direct breakthrough from the transmitter,*

√*Able to make accurate measurements*,

√ *Covert* - i.e. we don't want the opponent to be able to see what frequencies we are using or which transmitters we are exploiting. Maybe a radome can solve this problem; or hiding the receiver antenna in existing buildings can help to maintain covert operation. We can also get away with very large antennas that way, including vertical apertures.

Under these constraints and after studying current PCL antenna designs, array antennas, which are theoretically phased array antennas, will be analyzed

for a possible PCL system. When designing an array antenna there are four main categories of considerations that are divided into subdivisions. These are:

1. Configuration
   a. Linear (1 Dimensional)
   b. Planar (2 Dimensional)
   c. Conformal (3 Dimensional)
2. Amplitude
   a. Uniformly Excited
   b. Non-Uniformly Excited
3. Phase
   a. Broadside Array
   b. Endfire Array
4. Element Spacing
   a. Equally Spaced
   b. Unequally Spaced

In this thesis research, the configuration will be fixed horizontal linear since the interested area will be DOA estimation in the azimuth. In order to make use of the mature array theory, only equally spaced elements will be studied for array structures. However, because Sidelobe Level (SLL) Reduction is an important issue for PCL systems, array designs with the non-uniformly excited elements will be a significant matter as well as ones with uniformly

excited elements. Since broadside arrays are desired phased array antennas, only broadside arrays will be studied.

1.6 Materials and Equipment

For this thesis, NECWin Plus [10] will be the main computer program to simulate and analyze the array antennas since it has so many advantages. In almost all of the antenna books, array antenna design considerations do not include real life complications such as the mutual coupling effects on the elements. This will lead the antenna engineer to incorrect and unwanted results. However, NECWin Plus takes these issues into account and delivers the most accurate outputs for the given conditions. Also, it is designed to allow users to quickly run antenna problems, view the structure of the antenna, and obtain graphical output by entering a few basic commands. Not only does it have a very simple user interface, but also it represents an outstanding value for the antenna engineer. Furthermore, describing the antenna geometry is as easy as entering numbers in a spreadsheet and in order to ensure that your geometry is correct; you can view the antenna structure with Necvu. Wire antennas are the only design structures for NECWin Plus, as we do not want the PCL system to be expensive.

Besides NECWin Plus, Antenna Pattern Visualization Program [11] and Antenna Solver [12] will be the complementary tools to support the simulation programs. These programs will help to verify the results of NECWin Plus and

will assist to make some of the computations easier, such as amplitude tapering techniques.

Within MATLAB Student Version 5.3, DBTlinkR2-19 signal simulation tool and some MATLAB codes generated and modified by Ahmet Ozcetin [13] will be used for to simulate the antennas for DOA estimations.

Chapter 2 - LITERATURE REVIEW

2.1 PCL Systems

2.1.1 Overview

Radar, which stands for Radio Detection and Ranging, is a device for detecting distant objects based on radio waves reflected from their surfaces. "*Monostatic Radar* operates by radiating energy into space and detecting the echo signal reflected from an object" [14]. "*Bistatic Radar* is the system in which the transmitter and the receiver are deployed at two separate locations; either or both of these locations can be changing with time" [15]. "When two or more receiving sites with common spatial coverage are employed, and data from objects in the common coverage area are combined at a central location, the system is called a *Multistatic Radar*" [1]. "*Hitchhiker*, on the other hand, uses a transmitter of opportunity, usually another radar, to detect and locate objects near the transmitting or receiving site" [1]. Therefore, *Passive Coherent Locator (PCL)* can be justified as a sort of bistatic radar, bistatic radar net or multistatic radar, which hitchhikes commercial broadcast signals such as television (TV) or Frequency Modulation (FM) signals.

2.1.2 Development of PCL

It is hard to credit someone with *inventing* the radar. The idea had been around for a long time, but the problem was that it was too advanced for the technology of the time until some works were initiated about it.

The whole basis for radar depends on the development of radio waves, and electricity is the foundation for that incident. Therefore, it would be realistic to state that this basis started with Benjamin Franklin when he proved in 1752 that electricity could be harnessed and controlled, and conducted from one point to another.

On the other hand, "the basic concept of radar was first demonstrated by the classical experiments conducted by the German Physicist, Heinrich Hertz, from 1855 to 1888. He showed that radio waves could be reflected from metallic objects and refracted by a dielectric prism" [14]. His work was based on the electromagnetic theory that was proclaimed by Maxwell in 1864.

Since Hertz built his work on theoretical effort, its practical application was the job of other engineers. In early 1900's, Christian Hulsmeyer, a German engineer, applied this theory and developed an instrument that successfully detected ships. "Soon after, in 1904, Hulsmeyer obtained a patent in England and other countries with his device, that would today be known as a monostatic radar" [14].

"The concept of a bistatic radar was first documented in the August 1917 edition of *The Electrical Experimenter*, when its editor, Hugo Gernsbach,

interviewed Nikola Tesla on methods of subjecting (submerged) enemy submarines" [1]. Tesla's theory explicitly accounted for the idea of not only bistatic radar, but also multistatic radar. "However, it wasn't until 1922 when the first application of bistatic radar was accidentally discovered by A. Hoyt Taylor and Leo C. Young of the Naval Research Laboratory in Washington D.C. " [14].

Idea of using radar for military purposes came into play during the 1930s, when some European governments started to worry about the situation developing in Europe. They decided that some form of warning system was needed as part of the defense of their countries.

After the British Government asked him about the possibility of using radio waves to help shoot down enemy planes, Sir Robert Watson Watt developed the first radar system, called a Radio Direction Finding System, in 1935. By 1940, Britain and the U.S. were using radar not only as a defensive weapon but also as an offensive weapon. During World War II, radars were known as a *magic eye* since it could detect planes through darkness, fog, and even in the worst storms.

Except for Hulsmeyer's radar, all early radar demonstrations can be considered as bistatic radar. Although their receiver and transmitter antennas were in almost the same location, these antennas were independent of each other. "The duplexer, invented in 1936, allowed alternation of transmission and reception at the same antenna while providing needed transmitter/receiver

isolation" [16]. Soon after, monostatic radars completely replaced the bistatic radars, which caused bistatic systems not to be the point of interest until the late 1950s.

"The first resurgence occurred in the 1950s, when bistatic radars were developed and deployed again as forward scatter fences, as semi-active homing missiles, and as precision test range instrumentation and satellite tracking systems" [1]. During the same years, the technology of low observables became a serious consideration in electronic warfare. Moreover, it was the first time that the United States experimented with the Radar Cross Section (RCS) and geometry of an object could affect the detection capability of the radar.

"Development of the Anti Radiation Missile (ARM) was probably the event that triggered the second bistatic resurgence in the 1970s and 1980s." [1]. The idea was to locate the transmitter away from the Forward Edge of Battle Area (FEBA), so to reduce the risk of getting hit by ARM. Moreover, the fact that the bistatic geometry reduced the efficiency of advanced and most recent deceptive jamming techniques, urged radar engineers to improve bistatic radars.

"However, until about 1980, bistatic radar research appears limited to a relatively small amount of work devoted to use of co-operative radar transmissions" [17]. Some radar engineers examined the bistatic system geometry and performance thoroughly, and they all agreed on the fact that monostatic radars were superior to bistatic radars. Nevertheless, they admitted

that the bistatic systems had some better aspects than monostatic systems, such as covert operation, ability to detect low observables, etc.

While the developments in radar technology were improving rapidly, IBM engineers came up with an idea to expand its computer market into the radar market. After thinking of the possible options meticulously, IBM radar division scientists took over the idea of identifying the flying objects by detecting the return commercial broadcast signals from these objects. With this idea, Passive Coherent Locator (PCL) concept literally came into existence.

"The first mention of PCL technology is to be found in classified Advisory Group for Aerospace Research and Development (AGARD) conference proceedings from 1985. This paper describes the initial studies addressing the problem of an airborne passive receiver system that exploits television transmitters" [18].

2.1.3 The Features and the Characteristics of a PCL System

A Passive Coherent Locator is basically a *passive system* that takes the advantage of Radio Frequencies (RF), such as television or FM radio broadcasts that already exist in the environment. In other words, it can be specified as *bistatic radar* since the transmitter is not a part of the system. The system takes advantage of coherent processing techniques, which are measuring and processing both amplitude and phase of the received signal, via manipulating

other transmission sources; therefore, it is called Passive Coherent Locator (PCL). The basic configuration of PCL is illustrated in Figure 4.

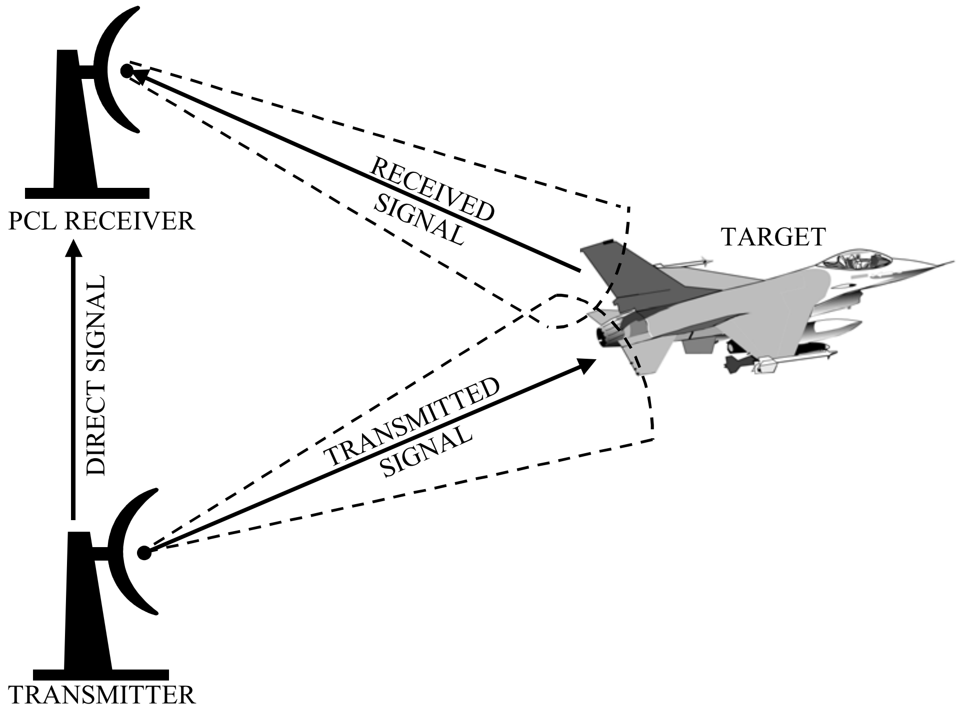

Figure 4: Basic Configuration of a PCL System

A basic bistatic configuration, one receiver and one transmitter, is enough for object detection. However, it is possible to detect, locate, and even identify the object by using multiple receivers and/or multiple transmitters. In order to eliminate or reduce the ambiguities in range, doppler, and bearing, a PCL system should use more than one illumination source and receiver. In other words, multistatic configuration yields a more robust, more redundant, and more powerful PCL system. "For single receiver and single transmitter configuration to be effective, the gain of the receiver antenna in the direction of interest needs

to be far greater than that in the direction towards the transmitter of opportunity” [19].

Compared to typical radar systems, PCL will exploit low frequency signals that are already in the space. Furthermore, PCL systems are to deal with the low power signals that have low Signal to Noise Ratio (SNR).

“A sensitive radar must somehow prevent the transmitter signal from directly entering the receivers. In most radars this isolation is performed in the time domain, by enabling reception during a substantial period when the transmitter is silent” [8]. In PCL systems either putting a distance between the transmitter and the receiver, a baseline; or allowing a natural or artificial obstacle, such as mountain or building respectively, between the transmitter and the receiver, achieves this isolation. Incidentally, achieving the isolation of the receiver from the transmitter is a trade-off for a high SNR. The longer baseline distance will cause a better isolation, yet a low SNR as well.

“The hardware requirements are for a well calibrated antenna system, a multi-channel low noise receiver system, a stable frequency reference and a high-speed accurate analog to digital converter” [18]. PCL systems mainly depend on software where conventional radars do not have this fundamental requirement. The most crucial stage for PCL systems is the complex digital signal processing that is used for software architecture.

“It is necessary to provide synchronization between transmitter and receiver in respect of (i) instant of transmission pulse, (ii) transmit antenna

azimuth, and (iii) transmit signal phase" [5]. "Additionally, a coherent reference for Moving Target Indicator (MTI) cancellation may be obtained from close-in stable clutter echoes" [20].

2.1.4 Importance of PCL for Military

Since PCL systems are mainly developed for military usage, it is natural that someone expects crucial benefits from this new design. In fact, PCL is mainly designed for military purposes in order to overcome the problems that are present with conventional radar systems.

The first significant advantage is the low cost of the whole system. Because there is no need to build or operate a high-power transmitter and because the system is highly dependent on software programming rather than hardware requirements, the cost of a PCL system is anticipated to be cheaper.

Another benefit can be stated as the manipulative covert operation. Since a PCL exploits the *transmitters of opportunity*, there is almost no risk of being detected. In other words, as there is no Radio Frequency (RF) emitting from the system itself, there is nearly no jeopardy of getting caught by detection. This fact leads the system to operate more efficiently. The fact that PCL receiver antennas are mostly Yagi antennas that look exactly like TV receiver antennas or array antennas hidden on the buildings makes the system almost invisible.

Last but not the least advantage is the truth that there isn't any need for the frequency assignment even though it is a new system. "It is difficult to get

frequency allocation for radars in the Very High Frequency (VHF) and Ultra High Frequency (UHF) band and it would be therefore useful to exploit existing signals" [21].

Unfortunately, the theory of 'You have to pay for the beauty you get!' works for PCL system as well. Some disadvantages show up as well as advantages. "The major disadvantages with this system concept probably lie in the limitations set by the transmitted RF signal" [21].

There is no way to control all the broadcast stations that are used as transmitters of opportunity, which implies no control over the transmitted power. This fact is undesirable especially in a war scenario, since it may cause the whole system to become useless in case of transmission cut off.

As the transmitted Signal-to-Noise Ratio (SNR) is fairly low, it is inevitable that dynamic range will be reduced compared to conventional radars. Thus, the coverage area and siting are decreased undesirably considering the military purposes.

Since low cost and covertness are the primary needs for PCL systems, this fact results in not manipulating the receiver aperture itself. For this reason, resolution for object location and identification are degraded.

Despite the fact that there are some advantages and disadvantages introduced by this new system, researchers have been trying various compromises to find out the most effective PCL design. Below are some of them.

2.1.5 Currently Known PCL Systems

There are only a few known PCL systems that are operating successfully. They take some different as well as some similar approaches to the problems.

The first study was accomplished by Griffiths and his colleagues in London in 1985 under the name of *Television-based Bistatic Radar*. Basic configuration of the system was bistatic and it was exploiting a UHF television transmitter as the illuminator. "The experimental system used two parallel receiver channels which were built around standard commercial tuner and Intermediate Frequency (IF)" [5]. They used 10 element Yagi and 17 element Yagi antennas to provide the reference signal and to achieve the echo reception respectively. Baseline distance, which is the distance between the transmitter and receiver, was 12 km and signal processing was non-real time operation. They explored several UHF television frequencies and observed the *range* and *bearing* parameters of the object. Moving Target Indicator (MTI) was examined as a possible implementation. With this first PCL concept, they concluded their work by stating "while television transmissions are in several ways not ideal for illuminators of opportunity, and require substantial processing to extract object echoes, a system of adequate dynamic range using real-time crosscorrelation would represent an intriguing prospect" [5]. This obsolete PCL system's performance was not so efficient and it had occasional detections and many false alarms.

The second study began right after IBM sold the passive radar research to Lockheed Martin. Although it was IBM scientists who used the *PCL* term first, Lockheed Martin put this study into practice in the early 1990s under the name of *Silent Sentry*. Basic configuration of the system was a bistatic net and the baseline distance was 50 km. "Silent Sentry is a single receiver, multistatic illuminator surveillance system, which determines precise three-dimensional object trajectories, and which provides continuous coverage of the airspace" [6]. The first version of the system was exploiting the television signals and it had a non-real time processor. However, the second version of the system, which is *Silent Sentry II*, exploits the Frequency Modulation (FM) signals and signal processing is implemented in real time. "Silent Sentry II has currently two configurations: the Fixed Site System (FSS) and the Rapid Deployment System (RDS)" [6]. This system has a linear array antenna that consists of six dipole elements and it can successfully acquire the range, the doppler and the bearing of the object parameters. "Silent Sentry has some inherent features and unique capabilities such as surveillance for challenging objects, excellent altitude coverage, inherent survivability, effective all weather operation and low system cost" [6]. However, all of the information given here has not been confirmed or verified, since Lockheed Martin's PCL work is classified. Also, Silent Sentry II is for sale in US markets at $3-5 million per basic unit.

The British scientist Paul Howland [17] is the designer of the next study, which was accomplished in England in 1995. It is known as *Television-based*

Bistatic Radar II and it used television transmitters as the opportunity of illumination source. Even though the system was designed as a forward detection fence, Paul Howland noticed that it was able to detect objects within 75 km off the baseline when operated. The baseline was chosen as 150 km to help suppressing the unwanted effects of direct path coming from transmitter to receiver. This system is mainly exploiting television signals where it is capable of exploiting Continuous Wave (CW), Amplitude Modulation (AM), narrowband Pulse Modulation (PM) or narrowband FM signals. "Howland's PCL system uses a pair of eight-element Yagi antennas, which are horizontally spaced about 0.6 wavelengths apart" [7]. These Yagi antennas are placed 18m above the ground to reduce the multipath effect. Signal processing is implemented in non-real time, and the bearing and the doppler of the object are acquired. With this currently developed system, most of the high and medium altitude objects were detected successfully where only one-third of them could be tracked.

Another known PCL system is called *Manastash Ridge Radar* developed by John Sahr at the University of Washington in the late 1990s. Baseline was chosen as 100 km between the main receiver and the transmitter. "However, performing the signal processing requires knowledge of the transmitted signal; therefore, a second receiver is located near the transmitter simply to record the actual broadcast" [8]. "Commercial FM broadcasts near 100 MHz illuminate the natural environment with continuous and high power illumination, which are superb for radar applications by fortunate" [22]. Manastash Ridge Radar, which has a basic

bistatic configuration, can acquire the range and the doppler parameters from the object. For this system a single channel Yagi antenna is used by the receiver. As object location is not needed for this experiment, range resolution is not urgent where doppler resolution is the key to the system. Detection of aircraft and meteor trails up to 250 km has been achieved successfully with Sahr's system that is still being used and developed.

Although these systems have been working properly, there is still a requirement to improve PCL technology.

2.1.6 Conclusion

Although PCL system is developed to overcome the handicaps of conventional radar system, there are some serious problems associated with its design. "Because PCL systems still have some typical issues, such as track initiation latency, track initiation efficiency, and spurious tracks; they are generally not acceptable for air defense yet" [9]. Nevertheless, this new system is giving hope to be a leading development for radar technology.

2.2 Array Antennas

2.2.1 Array Background

It is hard to tell when the first work on the array antennas was done, but most of the activities on the array antennas were done in the 1920s. "During World War II, much array work was performed in the United States and Britain.

Interest in arrays returned in the early 1960s, with research projects at Lincoln and Bell Laboratories, General Electric, RCA, Hughes, and others" [23].

2.2.2 Array Factors and Basic Array Characteristics

An antenna is a device used for transmitting and receiving electromagnetic energy for systems. In some cases these goals may be served by an antenna consisting of a single element, which may be one of various types depending on operating frequency range, environment, economy, and many other factors. "When a particular application demands higher gain, a more directive pattern, steerability of the main beam, or other performance that a single element antenna cannot provide, an antenna made up of an array of discrete elements may offer a solution to the problem" [24].

"In most cases, the elements of an array are identical; this is not necessary, but is often convenient, simpler, and more practical. The individual elements of an array may be of any form (wires, apertures, etc.)" [4].

According to [24] and [4], in an array of identical elements, there are five parameters that are varied for controlling the shape of the overall pattern of the antenna:

1. the geometrical configuration of the overall array (linear, circular, rectangular, spherical, etc.)

2. the relative displacement between the elements

3. the excitation amplitude of the individual elements

4. the excitation phase of the individual elements

5. the relative pattern of the individual elements

On the other hand, "important array factors for the system designer are broadside pattern, gain versus angles, element input impedance, and efficiency" [23]. From the analysis viewpoint, the five parameters stated above are specified to determine these array factors. Alternatively, the synthesis problem is to determine these five parameters in such a manner that the array response will approximate a desired one as closely as possible under certain criteria.

2.2.3 Mutual Coupling

According to [4], when two antennas or antenna elements are near each other, whether one and/or both are receiving or transmitting, some of the energy that is primarily intended for one ends up at the other. The amount depends primarily on the radiation characteristics of each element, relative separation between the elements, and the relative orientation of each element.

In the transmitting mode, some of the energy scattered from one element can affect the other element due to non-ideal directional characteristics of that element. Therefore, part of the incident energy on one or both elements may be rescattered in different directions allowing them to behave as secondary

transmitters. This interchange of energy is known as *mutual coupling*, which complicates the analysis and design of an antenna.

On the other hand, in the receiving mode, the incident wave can be rescattered from one element and can affect the other element. This can again cause *mutual coupling* between the elements.

The effects of the mutual coupling on the performance of the array depends upon the antenna type and its design parameters, relative positioning of the elements in the array, feed of the array elements, and scan volume of the array. These design parameters influence the performance of the antenna array by varying its element impedance, reflection coefficients, and overall antenna pattern.

Chapter 3 - METHODOLOGY

3.1 Analysis and Design of an Antenna

In designing an antenna, the first thing to consider is how to physically construct the operational characteristics of the antenna. The analysis of an antenna, on the other hand, is completely reversed in this procedure: it is to find out the operational characteristics of an antenna for a given physical structure. But, of course there are some important issues to ponder while analyzing an antenna such as knowledge of antenna theory, working experience and knowledge in using computer programs.

Alternatively, array antenna analysis is mainly to obtain an Array Factor (AF) for a given array configuration and element feedings.

3.2 Antennas Analysis Using NECWin Plus

3.2.1 NECWin Plus and Its Capabilities

According to [25], the Numerical Electromagnetics Code (NEC) is an outgrowth of a program developed in the 1970s, called the Antenna Modeling Program (AMP). There are different versions and NEC-2 is the most popular one considering the public domain, where NEC-4 requires a separate license for use. NEC in all its forms is a computer code for the analysis of the electromagnetic response of the antennas and other metal structures that uses method-of-

moments techniques for the numerical solution to integral equations for the currents induced on an antenna structure by sources or by incident fields.

NECWin Plus is an antenna-modeling program that uses a modified version of the NEC-2 core within an extensive array of input and output facilities. It has two objectives: First, it is designed to allow the user to accurately and easily develop an antenna model in the format required for NEC-2 calculations. Second, it provides a large number of output data options to allow the user to examine the NEC-2 data both tabularly and graphically, in order to ensure the most correct and complete analysis and interpretation. NECWin Plus is written for the Windows 95/98 environment.

NECWin Plus is capable of accurately modeling a wide variety of wire antenna geometries across a frequency span from Very Low Frequency (VLF) to Ultra High Frequency (UHF).

Since NECWin Plus is designed to allow users to quickly run antenna problems, view the structure of the antenna, and obtain graphical output by entering a few basic commands, it represents an outstanding value for the antenna engineer. It has a very simple user interface and describing the antenna geometry is as easy as entering numbers in a spreadsheet.

The method of analysis used by NECWin Plus requires that any antenna element be a collection of thin linear wires and that each be segmented within certain limits. Therefore, NECWin Plus is limited to modeling of wire antennas only.

NECWin Plus operates most reliably within a set of limiting conditions that the antenna engineer must observe. It also exhibits a number of special limitations that fall within the range where the user expects good results. Some of these limitations can be overcome by substituting modeling techniques that are nothing but simple modifications of model construction.

3.2.2 NECWin Plus Input and Output Data

3.2.2.1 NECWin Plus Inputs

Compared to NEC-2 version, NECWin Plus has automated features to enable the modeler to enter data more easily. It consists of four main windows that look like Microsoft Excel, which are used for processing input and output data. Since it is designed for Windows, it has a simple user interface while designing an antenna.

Figure 5 shows an example of the main input screen, which is called wires spreadsheet and used for numeric input of a wire antenna configuration. "All wire data is entered as a set of Cartesian coordinates in X, Y, and Z dimensions for each end of the wire" [25]. Besides, segment number, source and load properties, element material and diameter, and frequency specification data can be entered on this page.

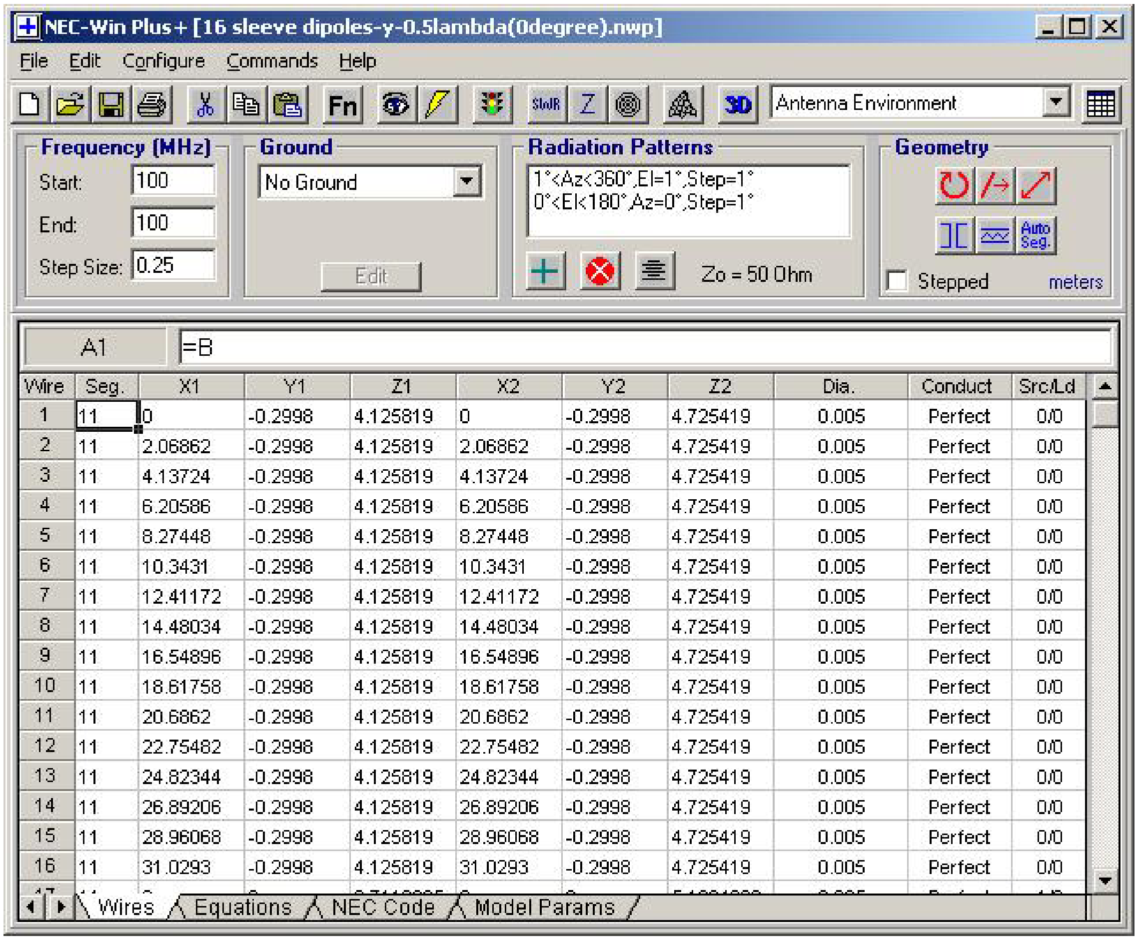

Figure 5: NECWin Plus Spreadsheet – Wires Screen (Example)

Figure 6 shows an example of further alternative spreadsheet available within NECWin Plus, which is used for symbolic entry. In this window, the user can designate each number with a parameter or an equation, in order to simplify design and modeling procedures of an antenna. It is especially helpful when the antenna geometry is tedious to model in the wire page.

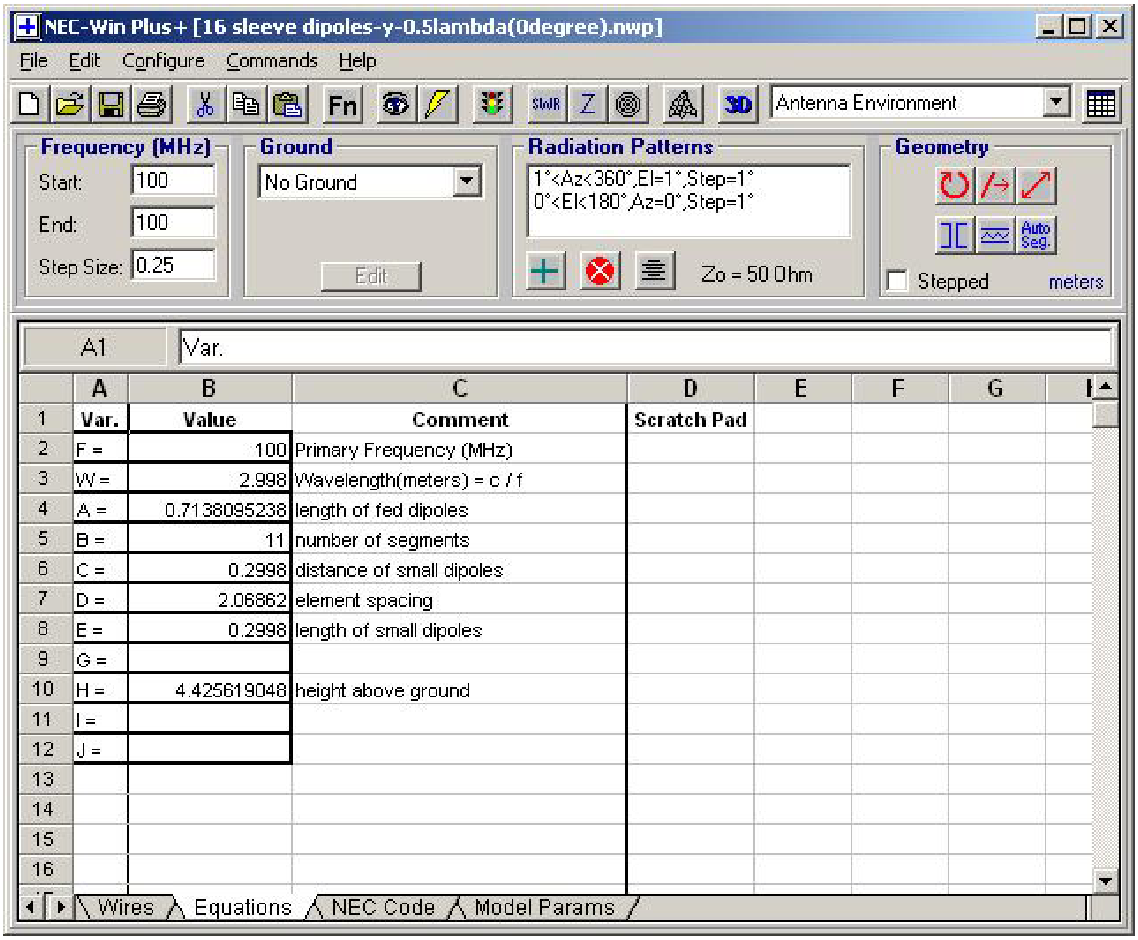

Figure 6: NECWin Plus Spreadsheet – Equations Screen (Example)

Figure 7 is the example of NEC Code screen that is used in NECWin Plus spreadsheet to get standard ASCII NEC-2 input file. These parameters can be used in NEC-2 version, which is not necessary for this thesis since NECWin Plus will be the main antenna software.

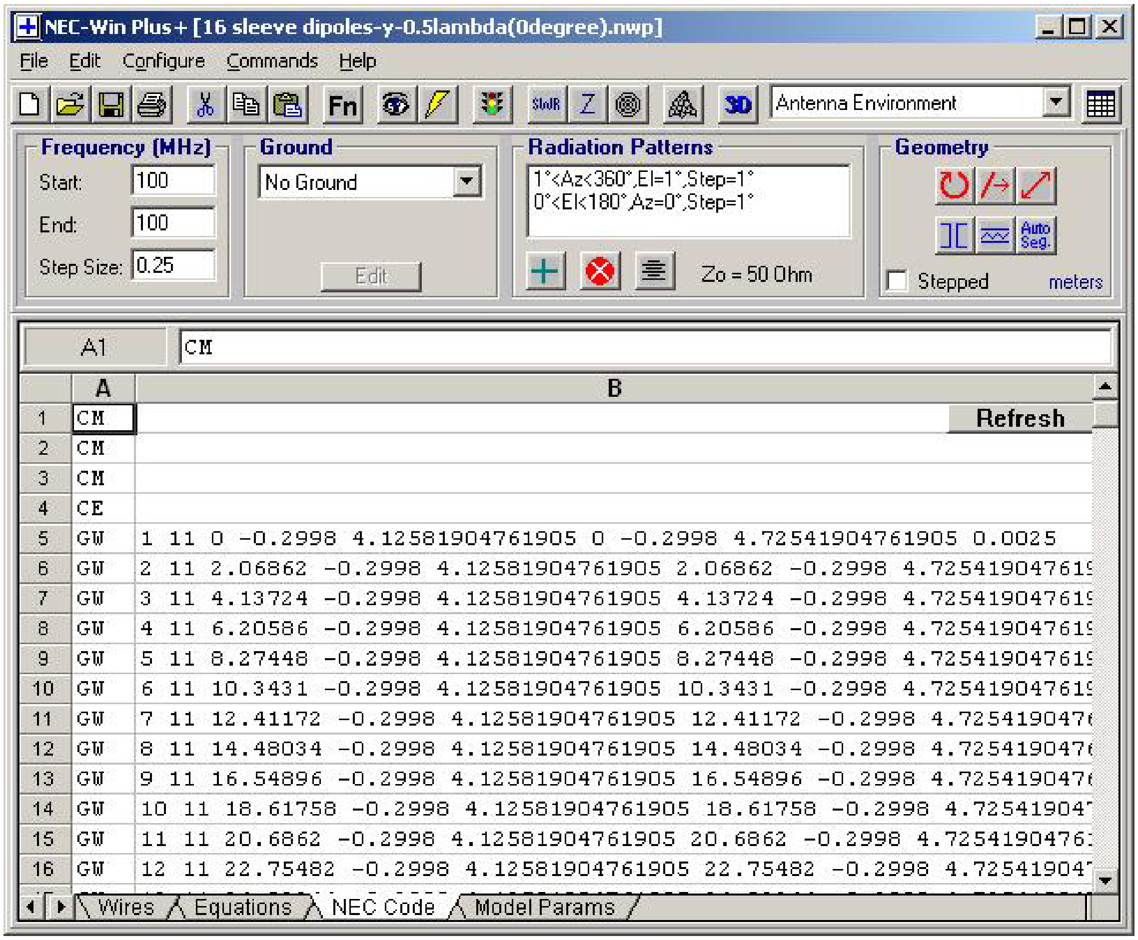

Figure 7: NECWin Plus Spreadsheet – NEC Code Screen (Example)

Figure 8 shows the example of a model parameters screen that defines the features of that specific antenna model. This screen is just to show the properties of that model to the user and it is not crucial while modeling.

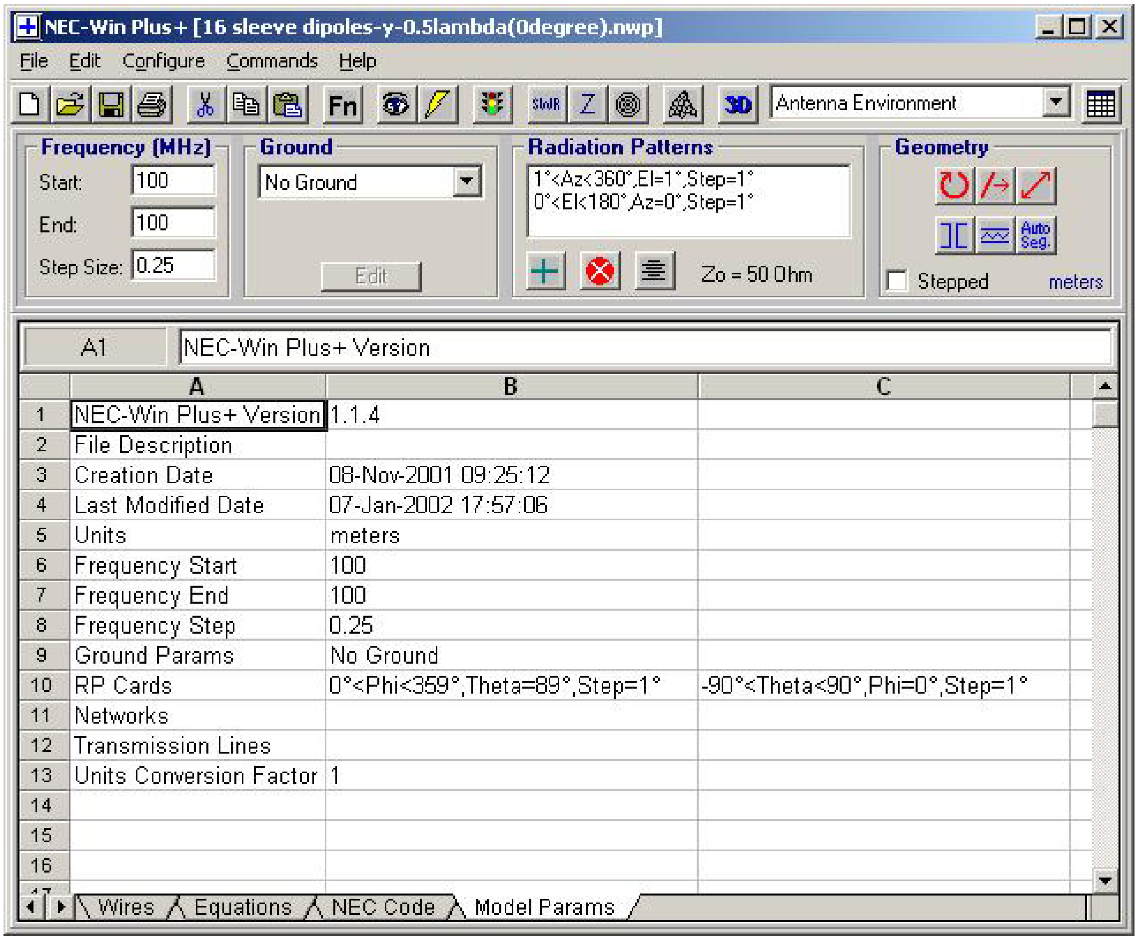

Figure 8: NECWin Plus Spreadsheet – Wires Screen (Example)

3.2.2.2 NECWin Plus Outputs

The outputs produced by NECWin Plus are the results of matrix calculations. There are three ways of viewing the results:

- *Tabular Data*
- *Polar Plots*
- *Rectangular Plots*

According to [25], NEC-2 produces its output data in a massive collection of ASCII tables in a single file where NECWin Plus permits the user to examine

the entire table or to view selected portions of the table. For example, it is possible to observe the currents along the wire as well as the source impedance for each frequency checked. These tabular data chains can be viewed one by one as well as altogether on a single sheet and some of these important output data that are on the table can be categorized as:

- Currents and Location*:* lists the coordinate and length information for each segment, then lists the calculated current information (real, imaginary, magnitude, and phase) for each segment.

- Far Field Ground Parameters: displays information about Linear/Radical Cliff ground planes and the Radial Ground Screen approximation.

- Network Data: lists information on transmission lines and networks. For transmission lines, the lengths, impedance, and shunt admittances are listed. For networks, the admittance matrix data are listed.

- Power Budget: lists the input power, radiated power, structure loss, network loss, and efficiency for each frequency step.

- Radiation Patterns: the horizontal, vertical and total power gains are listed. This also includes the polarization data for axial ratio, tilt, and sense and the E_θ and E_ϕ components of the electric field (magnitude and phase).

- Segmentation Data: lists the connection table for the model (how all of the segments are connected to each other).
- Source Input Parameters: lists the voltage, current, impedance, admittance and the power for each excitation source.
- Structure Impedance Loading: lists any loads (complex, parallel/series RLC) that are on the model and reports their values for each frequency step.
- Structure Specification: lists the geometry for each wire.
- VSWR: the Voltage Standing Wave Ratio for the input of an antenna at the voltage source connection is calculated based on the input impedance of that antenna.

Moreover, NECWin Plus offers the user the opportunity to study the outputs in a graphical format including both rectangular and polar formats. There are only some necessary graphical output data within NECWin Plus. First one is the Polar Plot of the radiation pattern of the specific antenna both in elevation and azimuth. Figure 9 shows an example of a 16-element dipole array antenna azimuth radiation pattern.

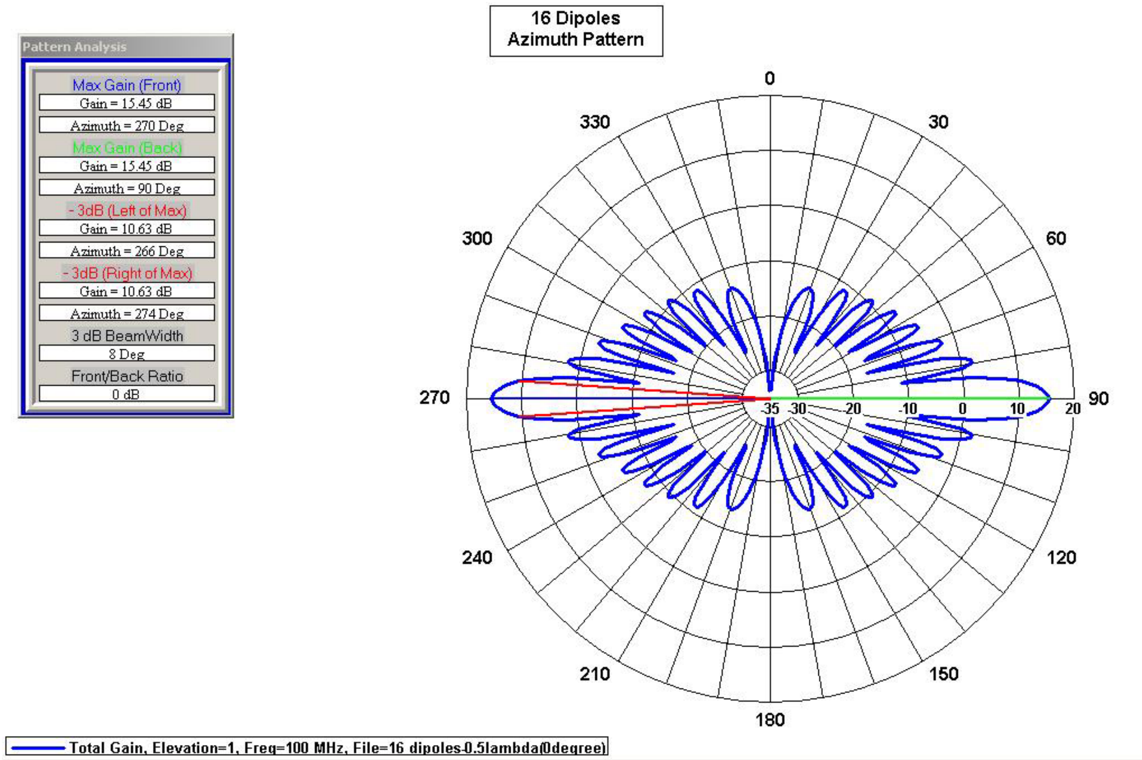

Figure 9: Polar Plot of an Azimuth Pattern (Example)

Figure 10 is an example of elevation pattern polar plot, which is the same antenna with the previous one (16-element dipole array).

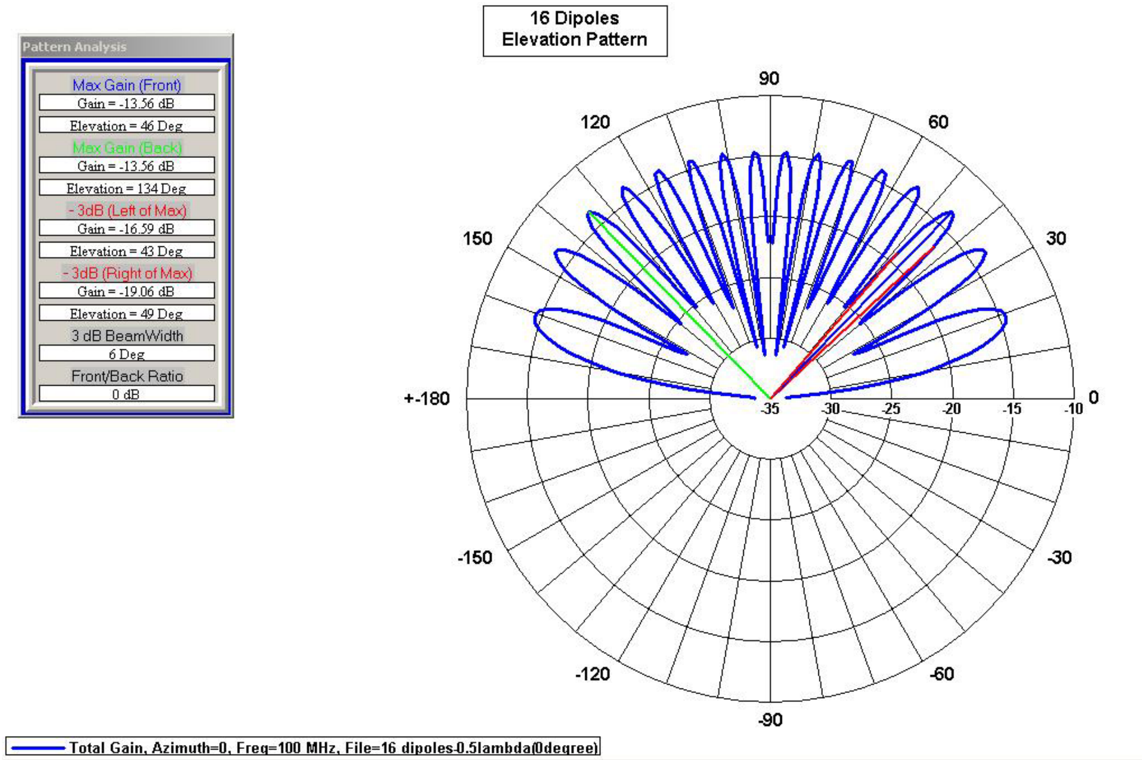

Figure 10: Polar Plot of an Elevation Pattern (Example)

Besides polar plots, NECWin Plus also offers rectangular plot possibilities, which will be helpful to the user. The Voltage Standing Wave Ratio (VSWR) vs. Frequency, and Input Impedance vs. Frequency are these rectangular plots that are useful while modeling an antenna. The VSWR for the input of an antenna at the voltage source connection is calculated based on the input impedance of that antenna. Figure 11 is an example of a rectangular plot, which is a VSWR vs. Frequency of a 16-element dipole array antenna operating around 100MHz.

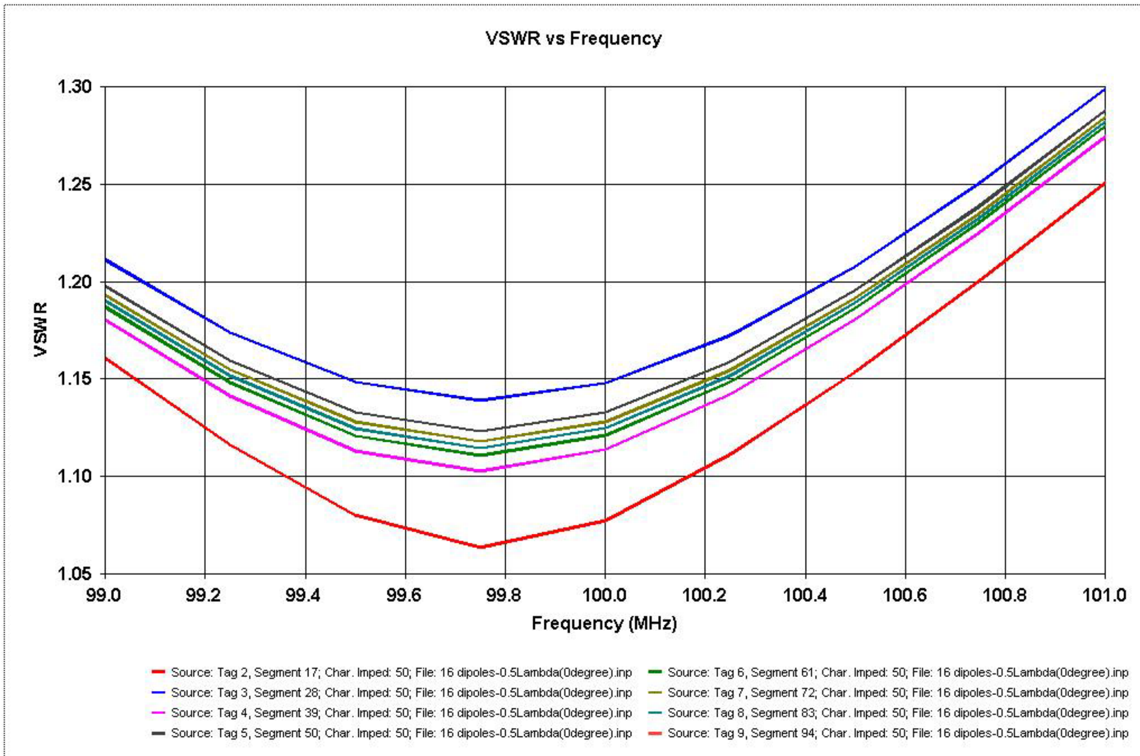

Figure 11: Rectangular Plot of VSWR vs. Frequency (Example)

In this figure, each line represents one element respectively. Since there is symmetry for 16 elements, only 8 of the elements (1 through 8) are taken into consideration and their VSWR values are shown.

Similarly, Figure 12 shows the input impedance of the same antenna with respect to its real and imaginary parts. Again, each line represents one element and values of the 8 of the elements (1 through 8) are shown.

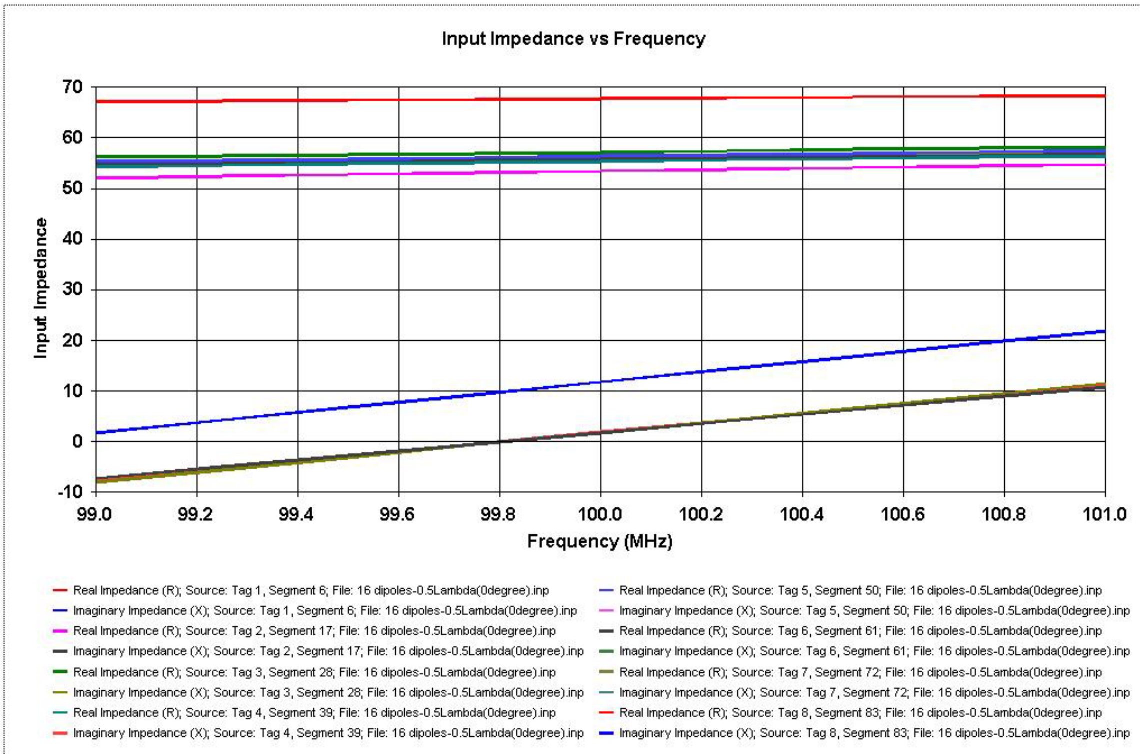

Figure 12: Rectangular Plot of Input Impedance vs. Frequency (Example)

Another important featured output for NECWin Plus antenna simulation program is the ability to view the 3-dimensional radiation pattern of an antenna. It enables the user to observe the radiation characteristic of the antenna in X, Y and Z coordinates at the same time. Figure 13 shows an example of 3-dimensional radiation pattern of a 16-element dipole array antenna.

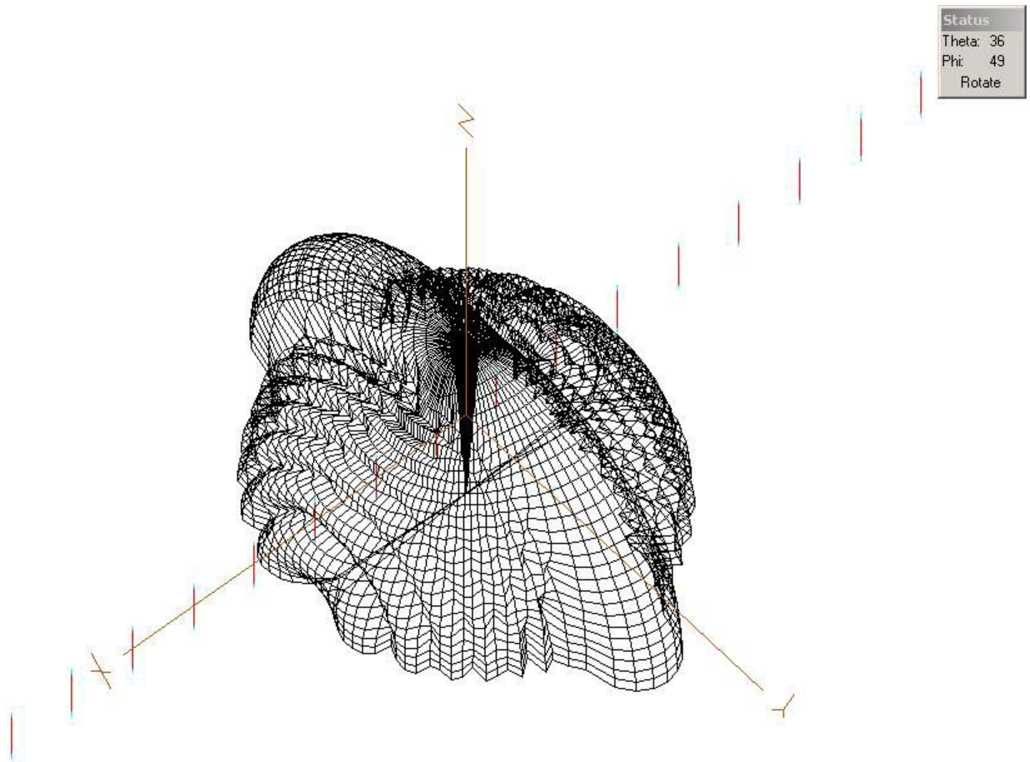

Figure 13: 3-Dimensional Radiation Pattern (Example)

"These results and outputs calculated by NECWin Plus are extremely useful and reliable to the user who wants to design, simulate or analyze an antenna in the computer world" [25].

3.2.3 Careful Model Construction with NECWin Plus

There are series of modeling guidelines and suggestions that will enable the user to avoid most of the common pitfalls in antenna model construction. These guidelines correspond to traps that can befall a user anytime while constructing an antenna. According to [25], these guidelines are:

Guideline 1: Use adequate segmentation for the frequency and element length. The convergence test, which sets certain limits to the lowest number of segments that should be used per half wavelength (the segmentation density), is a good approximation to identify the number of segments. General rule of thumb is to use around 11 segments per half wavelength of wire.

Guideline 2: Ensure that the feedpoint is where you want it. Changing the segment number on the spreadsheet will not change the source location on the wire, which will cause miscalculations. Therefore, after every modification on the antenna model, the source placement should be revised.

Guideline 3: Determine the correct azimuth angle for an elevation plot or the correct elevation angle for an azimuth plot.

Guideline 4: To the degree feasible, equalize all segment lengths within models. Although there are few exceptions, the guideline applies to all parallel wires, including those more widely spaced in parasitic beams, and to wires joining at their ends; for example, in closed geometry structures. "As a practical note, this guideline may require judicious violation on occasion" [25].

Guideline 5: Model each antenna element in a consistent pattern throughout the antenna from one end to the other. Doing so will result in more

precise and trustworthy outputs since the current from one point to another will be smooth and in an orderly manner.

Guideline 6: Correctly establish all antenna element ends.

Ultimately, careful model construction is a combination of some issues, which will lead the user to design more accurate and reliable configurations. These issues are:

- Developing good modeling practices,
- Being careful with the details, and
- Using features offered by the program to ease the burden.

3.2.4 Source Types and Placement

In NECWin Plus, there are two kinds of energy sources that a user can place on the antenna source point: *Voltage Source* and *Current Source*. According to [25], the most fundamental energy source for an antenna modeled in NEC-2 is the voltage source. By selecting an arbitrary voltage and placing it at the antenna source point, NEC-2 can calculate all of the most significant electrical parameters of an antenna, using the calculation of mutual impedances as a basis. Since current at any point on the antenna will be proportional to the impedance for any given voltage, using a value of 1 Volt suffices for most simple models. In most antennas, this will result in very low values of current, so it is

recommended to choose higher voltages, such as 100 Volt, to elevate the current values. Such moves are strictly for convenience in reading current magnitude and make no difference to current distribution or current phase at any point on the antenna.

However, array antennas require multiple sources rather than a single source in the model. "Phased array antennas, both vertically and horizontally polarized, are prime within this group, which also includes arrays of independently fed dipoles and the like. In a phased array, the feed system is often a calculated length of transmission line between one element that is also connected to the source of energy and one or more other elements. All of the elements are driven, and transmission line functions as a means of transforming the magnitude and phase of the current to the other element" [25]. Therefore, for this thesis current sources will be the focal point on the analysis of array antennas.

3.3 Methodology for Array Antenna Analysis Using NECWin Plus

3.3.1 General Array Antenna Structure

This antenna will theoretically will work as a *receive-only phased array antenna*. Since transmitters of opportunity will be exploited there will be no transmitting within the system and as a result the antenna will be used for only listening mode. Therefore, there will not be any radiating elements; however, antenna elements will be used for the reception of an incoming signal from the

environment. These signals, which are electromagnetic waves, will induce currents on each element and these currents will be treated as sources- which are actually current sources in NECWin Plus- by using the reciprocity theorem, which represents the calculation or measurement of an antenna pattern in either transmitter or receiver case" [26].

Another important issue is that the antenna elements will be identical to each other. In other words, in each antenna design only one element profile will be used and the other elements will have the same length, diameter, and material as this element. All of these elements will be uniformly distributed on the X-axis.

By changing the progressive phase on each element, the main beam of the antenna will steer off boresight. There are two types of array antennas of interest here: broadside and end-fire. For this research, only broadside array antennas are involved in the analysis.

For this thesis, a PCL antenna is desired to be *vertically polarized*, since the transmitters of opportunities will be FM broadcast antennas, which are also vertically polarized. Doing so will prevent power loss due to polarization mismatch, i.e. "the polarization of the receiving antenna is not the same as the polarization of the incoming (incident) wave" [4].

Figure 14 shows that a typical n-element array antenna structure, which will be helpful for further discussion.

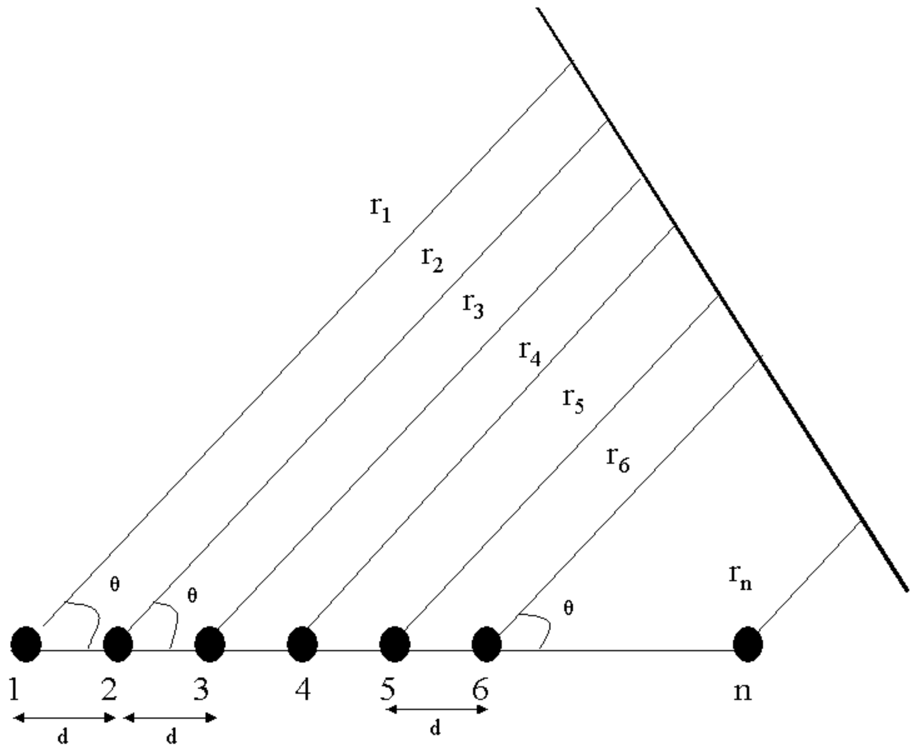

Figure 14: Typical Array Structure

3.3.2 Configuration of the Array

In general, Linear (1-Dimensional), Planar (2-Dimensional), and Conformal (3-Dimensional) are the configuration classes for an array design. For this research, we analyze and design only linear array antennas by simulating them in NECWin Plus. There are several reasons that led this decision:

- The most crucial interest in PCL designs is the Direction Of Arrival (DOA) for azimuth estimation. Linear array antenna is sufficient for this requirement.

- Linear array is more convenient, simple, and more practical for mathematical calculations, which is advantageous for complex algorithms used in PCL systems.
- There is no unclassified work done with array antennas for a PCL system, which one can study as a model.

Considering these facts, only linear array antennas are studied for this thesis research.

3.3.3 Element Spacing

Elements can be either equally spaced or unequally spaced in an array antenna design. For this research, only equally spaced elements within antenna designs for PCL systems are analyzed for simplicity. Spacing between the elements will be discussed in a further part of this thesis.

3.3.4 Number of Elements

The main purpose of using an array antenna design for a PCL system receiver is basically to increase the number of channels within the system, as it brings along some advantages that will be mentioned in Chapter 4. After consulting my thesis advisor and my sponsor, I decided to use 16 elements within the design for analysis of array antennas fore a PCL system. There are several reasons that led me to make this decision:

- Number of the elements in an array design can be either odd or even. However, in phased array designs even number is preferable since it gives better results due to symmetric distribution of the currents.

- DOA estimation mainly depends on the interferometry, and since the array antenna will be configured in 1-Dimension, 16 elements are good enough for DOA estimation in the azimuth.

- Since only FM waveforms will be the focal point, 16-element array can be optimal considering the size. Using more than 16 elements will produce a large size, which hampers the covert operation (16-element array with 0.5λ element spacing is around 45 meters).

3.3.5 Transmitters of Opportunity

In order to acquire the object estimations, there have been three different PCL systems with respect to the exploited signal:

1. <u>Narrowband PCL:</u> Audio or video carriers of the TV waveforms are used to acquire doppler and/or DOA estimations of the object.

2. <u>Wideband PCL:</u> Modulation spectra of FM waveforms are used to acquire range, doppler and/or DOA estimations of the object.

3. <u>Pulse PCL:</u> Pulsed radar signals are used to acquire estimations of the object.

Generally FM and TV stations have been exploited as transmitters of opportunities since there are many of them in the environment. These transmitters usually broadcast 24 hours a day, and their signals have some qualities that PCL systems can exploit.

For this research, the array antennas are analyzed which exploit only FM waveforms. There are several reasons under this decision:

- FM stations are worldwide and the signal waveform is the same all around the world; where TV signals may have different characteristics among different countries.
- FM broadcasting will continue in the future just like today, whereas TV broadcasting is now switching to either cable or digital broadcasting.
- The number of the FM transmitters is much more than number of TV transmitters.

Considering these issues FM broadcast signals will be utilized as the transmitted signal, which is 88MHz through 108MHz, for analysis of array antennas for a possible PCL system.

3.3.6 Element Amplitude Excitation

Array designs consist of elements with either uniform or non-uniform amplitude excitation. Both techniques have advantages and disadvantages while

applying to array antennas. With this research, these two different techniques will be analyzed for a possible PCL receiver antenna design.

3.3.6.1 Uniform Amplitude

According to [4], a uniform array of identical elements all of identical magnitude and each with a progressive phase is referred to as a uniform array, with the Array Factor (AF) given by:

$$AF = \sum_{n=1}^{N} e^{j(n-1)\psi} \qquad (3)$$

$$\psi = kd\cos\theta + \beta \qquad (4)$$

$$k = 2\pi/\lambda \qquad (5)$$

where, ψ = progressive phase,

λ = wavelength,

θ =: angle off boresight of an incoming signal

β = phase excitation between the elements,

d = distance between the elements.

Ignoring the phase, the uniform excited, equally spaced linear array will have the array factor as:

$$AF = \frac{\sin(N\psi/2)}{N\sin(\psi/2)} \qquad (6)$$

Of course, these formulations, which are in every antenna book, are calculated ignoring the mutual coupling effects among the elements. Therefore,

finding the Array Factor for a practical 16-element array will not be precise. However, NECWin Plus calculations do not neglect this important issue since it is vital in PCL system computations.

Consequently, to analyze the array antennas by using NECWin Plus, equal current amplitudes of 1 Ampere (as suggested in [25]) will be put on each element to simulate the receiver array antenna with equal amplitude elements.

3.3.6.2 Non-Uniform Amplitude

"The far-field pattern properties of most frequent concern to the array designer are the array sidelobe level, array gain, and beamwidth" [2]. All of these properties, which are even more important for a PCL receiver antenna, are influenced by the amplitude excitation of the array elements. This is accomplished by amplitude tapering which is a way of amplitude reduction on the elements towards the end.

According to [4], the array factor of array antennas with isotropic elements depends on the element number being odd or even. Mathematical expressions of Array Factors for both odd and even number of elements are given by:

$$\begin{aligned}(AF)_{2M}(even) &= \sum_{n=1}^{M} a_n \cos[(2n-1)u] \\ (AF)_{2M+1}(odd) &= \sum_{n=1}^{M+1} a_n \cos[(2n-1)u]\end{aligned} \tag{7}$$

$$u = (\pi d \cos\theta)/\lambda \qquad (8)$$

where, λ = wavelength,

θ =: angle off boresight of an incoming signal,

d = distance between the elements,

a_n = excitation coefficients.

Along with these formulas, there is only one necessary step remaining before applying an array antenna with non-uniformly excited elements to NECWin Plus: to determine the values of the excitation coefficients (a_n's).

There are different techniques of constructing array antenna elements with the non-uniform amplitudes. However, three of them Binomial, Dolph-Chebyshev, and Taylor are the most commonly used for array antenna designs. These three techniques will be analyzed for PCL systems, which will mainly achieve sidelobe level reduction.

In order to find the element excitation coefficient values, there are a series of computations as follows.

1. **<u>Binomial Array</u>**

"In order to determine the excitation coefficients of a binomial array, J. S. Stone suggested the function as" [4]:

$$(1+x)^{n-1} = 1 + (n-1)x + \frac{(n-1)(n-2)}{2!}x^2 + \frac{(n-1)(n-2)(n-3)}{3!}x^3 + \dots \quad (9)$$

The excitation coefficients of the Binomial Series Expansion for different n (number of elements) values are shown in Table 1.

Table 1: Excitation Coefficients for Different Number of Elements (Binomial)

Number of Elements																
n=1	1															
n=2	1	1														
n=3	1	2	1													
n=4	1	3	3	1												
n=5	1	4	6	4	1											
n=6	1	5	10	10	5	1										
n=7	1	6	15	20	15	6	1									
n=8	1	7	21	35	35	21	7	1								
n=9	1	8	28	56	70	56	28	8	1							
n=10	1	9	36	84	126	126	84	36	9	1						
n=11	1	10	45	120	210	252	210	120	45	10	1					
n=12	1	11	55	165	330	462	462	330	165	55	11	1				
n=13	1	12	66	220	495	792	924	792	495	220	66	12	1			
n=14	1	13	78	286	715	1287	1716	1716	1287	715	286	78	13	1		
n=15	1	14	91	364	1001	2002	3003	3432	3003	2002	1001	364	91	14	1	
n=16	**1**	**15**	**105**	**455**	**1365**	**3003**	**5005**	**6435**	**6435**	**5005**	**3003**	**1365**	**455**	**105**	**15**	**1**

These values are not normalized, since the end element excitation coefficients will become distinctly small when the number of the elements is increased. The values are boldface for the 16-element array, as these excitation coefficients are mainly used for this research. Other values for different numbers of elements will assist me in evaluating the consequences of using the Binomial Array in array designs.

Fundamentally, there will not be any sidelobes as a consequence of using the Binomial Array. However, applying Binomial Series in array models for PCL systems will be discussed and analyzed thoroughly in Chapter-4.

2. Dolph-Chebyshev Array

"Another technique is called the Dolph-Chebyshev Array (or just Chebyshev Array), which is basically a compromise between the Uniform Array and the Binomial Array, with its excitation coefficients are generated by the Chebyshev Polynomials" [4].

In Chebyshev Arrays, all the sidelobes are set to the same level, which makes it appealing in practical array design methods. Furthermore, "the Chebyshev Array is considered optimum in the sense that the first-null beamwidth is minimum for a specified sidelobe level or that the sidelobe level is minimum for a specified first-null beamwidth" [2]. "However, this statement is true for broadside arrays only with an element spacing no less than one-half wavelength or for ordinary end-fire arrays in which the element spacing is no less than one-quarter wavelength" [27]. This very important feature makes it a remarkable application for an array antenna design for a PCL system.

In order to determine the excitation coefficients of a Chebyshev Array there is a mathematical procedure as shown below:

I. Select the appropriate array factor as given in *Equation (6)* depending on the number of the elements.

II. Expand the array factor by replacing each cosine term with a series of cosine functions, such as:

m=0 cos(mu) = 1

m=1 cos(mu) = cos(u)

m=2 cos(mu) = cos(2u) = $2\cos^2(u) - 1$

m=3 cos(mu) = cos(3u) = $4\cos^3(u) - 1$

m=4 cos(mu) = cos(4u) = $8\cos^4(u) - 8\cos^2(u) + 1$

m=5 cos(mu) = cos(5u) = $16\cos^5(u) - 20\cos^3(u) + 5\cos(u)$

…and so forth.

III. Let cos(u) = z. Rewrite the array factor by replacing cosine terms with z, and relate each equation to the Chebyshev Polynomial ($T_m(z)$).

IV. Determine the point $z = z_0$ such that $T_m(z_0) = R_0$ (voltage ratio).

V. Substitute $\cos u = \frac{z}{z_0}$ in the array factor found in step II.

VI. Determine the excitation coefficients (a_n's) and normalize them.

By applying this procedure, the excitation coefficients of the Chebyshev Array with –26dB sidelobe level and –40dB sidelobe level for different n (number of elements) values are shown in Table 2 and Table 3, respectively. These two sidelobe levels will be adequate to analyze and evaluate Chebyshev Arrays for PCL systems.

Table 2: Excitation Coefficients for Different Number of Elements
(Dolph Chebyshev Array with SLL=-26dB)

Number of Elements																
n=1	1															
n=2	1	1														
n=3	0.905	1	0.905													
n=4	0.470	1	1	0.470												
n=5	0.474	1	0.632	1	0.474											
n=6	0.365	0.718	1	1	0.718	0.365										
n=7	0.384	0.690	1	0.562	1	0.690	0.384									
n=8	0.350	0.570	0.836	1	1	0.836	0.570	0.350								
n=9	0.372	0.552	0.808	1	0.536	1	0.808	0.552	0.372							
n=10	0.361	0.489	0.711	0.895	1	1	0.895	0.711	0.489	0.361						
n=11	0.384	0.478	0.686	0.872	1	0.523	1	0.872	0.686	0.478	0.384					
n=12	0.383	0.440	0.624	0.795	0.928	1	1	0.928	0.795	0.624	0.440	0.383				
n=13	0.406	0.432	0.604	0.770	0.908	1	0.516	1	0.908	0.770	0.604	0.432	0.406			
n=14	0.410	0.407	0.562	0.715	0.848	0.947	1	1	0.947	0.848	0.715	0.562	0.407	0.410		
n=15	0.433	0.401	0.547	0.693	0.826	0.932	1	0.512	1	0.932	0.826	0.693	0.547	0.401	0.433	
n=16	**0.440**	**0.383**	**0.517**	**0.652**	**0.777**	**0.883**	**0.960**	**1**	**1**	**0.960**	**0.883**	**0.777**	**0.652**	**0.517**	**0.383**	**0.440**

Table 3: Excitation Coefficients for Different Number of Elements
(Dolph Chebyshev Array with SLL=-40dB)

Number of Elements																
n=1	1															
n=2	1	1														
n=3	1	0.980	1													
n=4	0.375	1	1	0.375												
n=5	0.332	1	0.688	1	0.332											
n=6	0.200	0.618	1	1	0.618	0.200										
n=7	0.190	0.571	1	0.595	1	0.571	0.190									
n=8	0.146	0.418	0.759	1	1	0.759	0.418	0.146								
n=9	0.145	0.389	0.716	1	0.557	1	0.716	0.389	0.145							
n=10	0.125	0.315	0.580	0.839	1	1	0.839	0.580	0.315	0.125						
n=11	0.127	0.298	0.544	0.802	1	0.537	1	0.802	0.544	0.298	0.127					
n=12	0.117	0.257	0.463	0.690	0.886	1	1	0.886	0.690	0.463	0.257	0.117				
n=13	0.119	0.246	0.437	0.654	0.856	1	0.526	1	0.856	0.654	0.437	0.246	0.119			
n=14	0.114	0.221	0.386	0.577	0.765	0.916	1	1	0.916	0.765	0.577	0.386	0.221	0.114		
n=15	0.117	0.214	0.367	0.547	0.731	0.891	1	0.519	1	0.891	0.731	0.547	0.367	0.214	0.117	
n=16	**0.114**	**0.196**	**0.332**	**0.493**	**0.661**	**0.816**	**0.935**	**1**	**1**	**0.935**	**0.816**	**0.661**	**0.493**	**0.332**	**0.196**	**0.114**

These values are normalized with respect to the center element since the end element excitation coefficients are reasonable when the number of the elements is increased. The values are boldface for the 16-element array, as these excitation coefficients are mainly used for this analysis. Other values for different number of elements assist to evaluate the consequences of using Chebyshev Arrays in array designs.

Fundamentally, all sidelobe levels will be the same for the Chebyshev Array. However, applying Chebyshev Arrays in array models for PCL systems will be discussed and analyzed thoroughly in Chapter-4. The results of the simulations will be shown and evaluated within NECWin Plus.

3. Taylor Array

"In spite of its desirable properties, the Dolph Chebyshev pattern is seldom used for radar antennas since it is unrealizable with arrays containing other than a small number of elements" [14]. In Chebyshev arrays, as the antenna size increases, excitation coefficient values of the end elements become so small that it can be unrealizable. "For some applications, such as radar and low noise systems, it is desirable to sacrifice some beamwidth and low inner minor lobes to have all the minor lobes decay as the angle increases on either side of the main beam" [4]. "The Dolph Chebyshev distribution is optimum in the sense that it yields the narrowest beamwidth for a given sidelobe; however, it

is not optimum in terms of aperture efficiency for a given sidelobe level" [2]. Therefore, the Taylor distribution, which is more practical to apply to radar antennas, yields a pattern that is an optimum compromise between beamwidth and sidelobe level.

Basically, the Dolph Chebyshev Array design yields minor lobes of equal intensity while the Taylor Array produces a pattern whose inner minor lobes are maintained at a constant level and the remaining ones decrease monotonically. "Compared to the Dolph Chebyshev Array, the Taylor Array has a 12 to 15% wider main beam. But such a loss in beamwidth is a small penalty to pay since the extreme minor lobes decrease as 1/u" [4].

There are two main Taylor Arrays used for SLL reduction: *Taylor One Parameter*, and *Taylor n-bar (*$\bar{n}$*) Aperture Distribution.*

According to [4], in order to determine the excitation coefficients of a Taylor One Parameter Array, the excitation coefficients can be derived from:

$$I_n(z') = \begin{pmatrix} J_0\left[j\pi B\sqrt{1-\left(\dfrac{2z'}{l}\right)^2}\right] \ldots -l/2 \le z' \le +l/2 \\ 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots elsewhere \end{pmatrix} \tag{10}$$

where, J_0 = Bessel function of the first kind of order zero,

B = constant that is determined from the specified sidelobe level.

And the space factor associated with Equation 10 can be obtained by:

$$SF(\theta) = \int_{-l/2}^{+l/2} I_n(z') e^{j[kz'\cos\theta + \phi_n(z')]} dz' \qquad (11)$$

where, $\phi_n(z')$ = phase distribution along the source.

On the other hand, "the Taylor n-bar Distribution was developed as a compromise between the Chebyshev or ideal aperture with its constant level sidelobes, and the Taylor One Parameter Array" [23]. The purpose of this technique is to obtain higher efficiency while keeping the advantageous sides of a tapered distribution. According to [2], the excitation coefficients are given as:

$$A(x, A, \overline{n}) = \frac{1}{2\pi}\{F(0, A, \overline{n}) + 2\sum_{n=1}^{\overline{n}-1} F(n, A, \overline{n}) \cos(\frac{n\pi x}{L})\} \qquad (12)$$

$$F(n, A, \overline{n}) = \frac{[(n-1)!]^2 \prod_{m=1}^{\overline{n}-1} \left(1 - \frac{n^2}{\sigma^2\left[A^2 + (m-1/2)^2\right]}\right)}{(\overline{n} - 1 + n)!(\overline{n} - 1 - n)!} \qquad (13)$$

where, x = distance from center of aperture,

L = total length of aperture,

R = design sidelobe voltage ratio,

$\overline{n}$ = number of equiamplitude sidelobes adjacent to main beam on one side,

A = 1/π arccosh(R),

$$\sigma = \frac{\overline{n}}{\sqrt{A^2 + (\overline{n} - 1/2)^2}}.$$

"In summary, the Taylor n-bar ($\bar{n}$) distribution is widely used because it gives slightly better efficiency and beamwidth than the Taylor one-parameter distribution, for the same sidelobe level" [23]. Therefore, for this research, only the Taylor n-bar distribution will be applied to array antennas, and this application will be called *Taylor Array*.

By applying this procedure, the excitation coefficients of Taylor Arrays with –26dB SLL for $\bar{n}$ = 5, and with –40dB SLL for $\bar{n}$ = 8, for different n (number of elements) values are shown in Table 4 and Table 5 respectively. These two sidelobe levels will be adequate to analyze and evaluate Taylor Arrays for PCL systems.

Table 4: Excitation Coefficients for Different Number of Elements
(Taylor Array with SLL=-26dB, $\bar{n}$ =5)

Number of Elements																
n=1	1															
n=2	1	1														
n=3	0.542	1	0.542													
n=4	0.487	1	1	0.487												
n=5	0.410	0.800	1	0.800	0.410											
n=6	0.403	0.725	1	1	0.725	0.403										
n=7	0.375	0.622	0.896	1	0.896	0.622	0.375									
n=8	0.374	0.578	0.840	1	1	0.840	0.578	0.374								
n=9	0.361	0.524	0.756	0.936	1	0.936	0.756	0.524	0.361							
n=10	0.361	0.498	0.708	0.897	1	1	0.897	0.708	0.498	0.361						
n=11	0.353	0.467	0.650	0.833	0.957	1	0.957	0.833	0.650	0.467	0.353					
n=12	0.354	0.452	0.615	0.791	0.928	1	1	0.928	0.791	0.615	0.452	0.354				
n=13	0.349	0.432	0.576	0.739	0.879	0.969	1	0.969	0.879	0.739	0.576	0.432	0.349			
n=14	0.350	0.423	0.551	0.703	0.844	0.947	1	1	0.947	0.844	0.703	0.551	0.423	0.350		
n=15	0.346	0.410	0.524	0.663	0.800	0.909	0.977	1	0.977	0.909	0.800	0.663	0.524	0.410	0.346	
n=16	**0.368**	**0.409**	**0.503**	**0.638**	**0.772**	**0.879**	**0.956**	**1**	**1**	**0.956**	**0.879**	**0.772**	**0.638**	**0.503**	**0.409**	**0.368**

Table 5: Excitation Coefficients for Different Number of Elements
(Taylor Array with SLL=-40dB, $\bar{n}$ =8)

Number of Elements																
n=1	1															
n=2	1	1														
n=3	0.357	1	0.357													
n=4	0.298	1	1	0.298												
n=5	0.210	0.706	1	0.706	0.210											
n=6	0.191	0.610	1	1	0.610	0.191										
n=7	0.162	0.480	0.839	1	0.839	0.480	0.162									
n=8	0.154	0.424	0.762	1	1	0.762	0.424	0.154								
n=9	0.141	0.357	0.649	0.900	1	0.900	0.649	0.357	0.141							
n=10	0.139	0.325	0.588	0.842	1	1	0.842	0.588	0.325	0.139						
n=11	0.139	0.287	0.515	0.752	0.932	1	0.932	0.752	0.515	0.287	0.139					
n=12	0.130	0.265	0.472	0.696	0.888	1	1	0.888	0.696	0.472	0.265	0.130				
n=13	0.125	0.241	0.424	0.627	0.826	0.951	1	0.951	0.826	0.627	0.424	0.241	0.125			
n=14	0.125	0.226	0.393	0.582	0.768	0.917	1	1	0.917	0.768	0.582	0.393	0.226	0.125		
n=15	0.122	0.210	0.359	0.531	0.707	0.859	0.963	1	0.963	0.859	0.707	0.531	0.359	0.210	0.122	
n=16	**0.121**	**0.200**	**0.336**	**0.496**	**0.664**	**0.818**	**0.936**	**1**	**1**	**0.936**	**0.818**	**0.664**	**0.496**	**0.336**	**0.200**	**0.121**

These values are normalized with respect to the center element since the end element excitation coefficients are reasonable when the number of the elements is increased. The values are boldface for 16-element array, as these excitation coefficients are used in array analysis. Other values for different number of elements assist in evaluating the consequences of using Taylor Arrays.

Fundamentally, sidelobe levels will decrease gradually. However, applying Taylor Arrays in array models for PCL systems will be discussed and analyzed thoroughly in Chapter-4. The results of the simulations will be shown and evaluated within NECWin Plus.

Weighting functions or excitation coefficients of each tapering method are displayed in Figure 15.

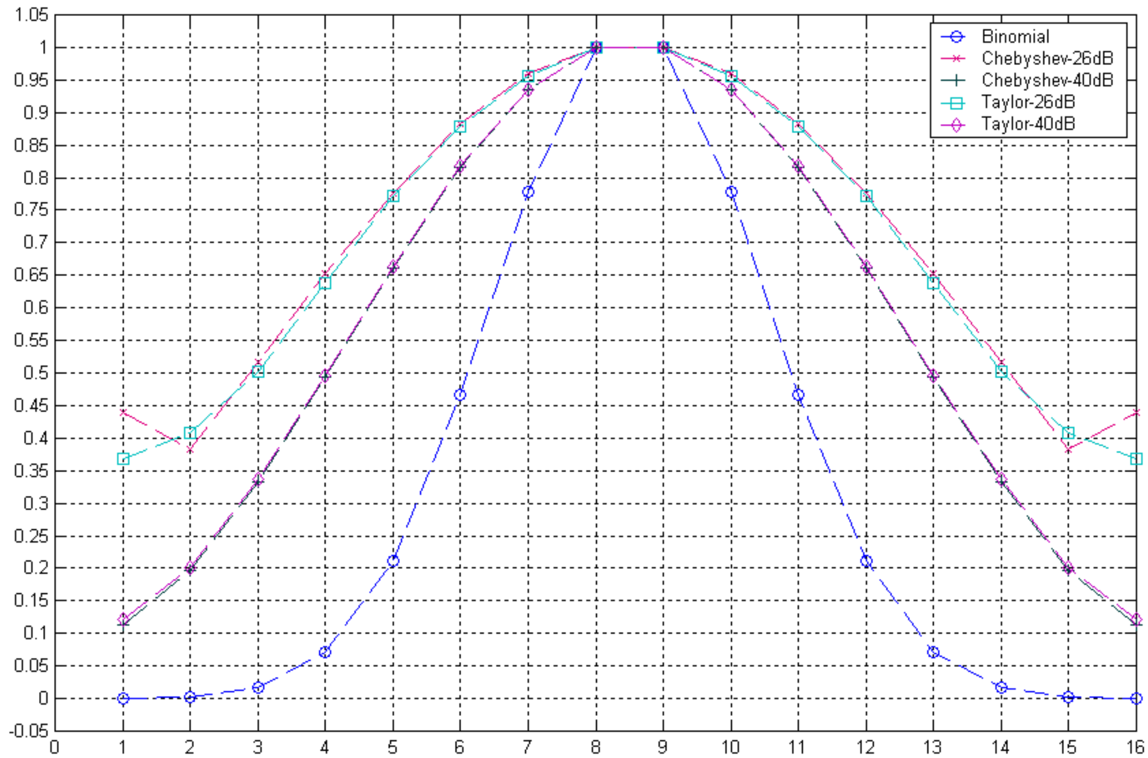

Figure 15: Excitation Coefficients for Each Tapering Method

It is obvious that decreasing the SLL causes the end elements to have smaller amplitude, which results in a wider main beam.

3.3.7 Feeding the Wire Antennas

"When connecting the antenna to a transmission line it is important to make effective use of all available power from the source (in the transmit case) and from the antenna in the receiver case" [26]. Consequently, there are two essential considerations:

1. The impedance match between the transmission line and the antenna,

2. The excitation of the current distribution on the antenna.

3.3.7.1 *Impedance Matching*

According to [26], a typical receiver circuit is shown in Figure 16, where

z_0 = impedance of the transmission line,

z_{ant} = impedance of the antenna,

z_{in} = input impedance.

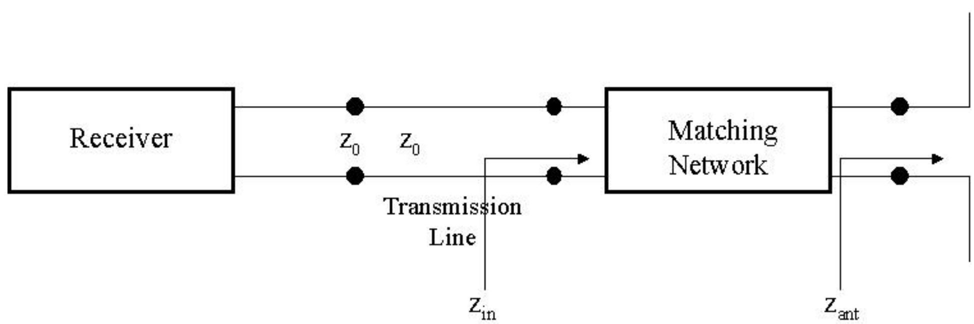

Figure 16: Typical Receiver Configuration

"Usually the receiver has an impedance equal to that of the transmission line, z_0. However, the antenna impedance, z_{ant} is frequently quite different from z_0, which can be a problem in some applications" [26]. If this mismatch is a problem within the application, there can be some remedial actions such as a *matching network* shown in Figure 16. Nevertheless, there are disadvantages to using matching network, i.e. match can be preserved only over a narrow band of frequencies, and loss will occur within the network. Therefore, it is not ideal to

use a matching network for PCL systems. However, matching the impedance of the antenna to the impedance of the transmission line, or characteristic impedance, will be a crucial requirement while designing array antennas in NECWin Plus. This will be achieved by closely monitoring the antenna impedance and VSWR values.

3.3.7.2 Current Balancing

"Many wire antennas are symmetrical (or balanced) in nature and, thus, the currents should also be symmetrical. But there can be an unbalanced current, which will result in an undesired radiation " [26].

"Transmission lines are also referred to as balanced and unbalanced. For example, coaxial transmission lines are unbalanced, which can result in no radiation at all" [26].

In order to adjust corrective measurements, a Balanced to Unbalanced (BALUN) transformer should be used to balance the current and/or the coaxial line within the system. The BALUN matches the impedance of the antenna to the transmission line. It may or may not provide the wide frequency range impedance transformation depending upon the configuration used.

3.4 Analysis and Evaluation Technique in NECWin Plus

As in every analysis technique, NECWin Plus has a course of action to analyze and evaluate an antenna. Namely, there are several variables that

directly have an effect on the objective functions. In order to show how these variables have affect the objective functions, it is helpful to begin with examining the features of these variables.

3.4.1 Variables

Several variables that can be exercised in NECWin Plus can be categorized as below:

- Element Shape
- Element Material
- Element Spacing
- Sub Arrays
- Media
- Sidelobe Level Reduction Techniques
- Diameter

It is advantageous to examine the properties of these variables, in order to understand how to utilize them in NECWin Plus.

3.4.1.1 Element Shape

There are several element shapes that can be used within the array design. However, since NECWin Plus is the simulation program that is used for this

thesis, all element designs will be *wires*. These wires can be of any different shape that we can use in the array. Yet, there are commonly used basic shapes that are used for analyzing antennas. These are:

1. Dipoles
2. Sleeve Dipoles
    a. Sub array is on the same axis with the main array
    b. Sub array is on a different axis than the main array
3. Loops
    a. Source is in the middle left side of the loop
    b. Source is in the middle lower side of the loop.
4. Diamonds

The methodology of designing these element shapes, and analysis and result of each design will be discussed in detail in Chapter 4.

3.4.1.2 Element Material

There are some common materials used in antenna construction and these materials can be simulated in NECWin Plus. Different material utilizations change the characteristics of the antenna since every material has a different conductivity or resistivity. In Table 6 are shown different conductivity and resistivity of common materials used in antenna construction according to [25].

Table 6: Conductivity and Resistivity of Common Antenna Materials

Material	**Resistivity Ohms/meter**	**Conductivity Siemens/meter**
Pure Silver	1.59E-08	6.2893E7
Copper	1.7241E-08	5.8001E7
Pure Aluminum	2.655E-08	3.7665E7
6063-T832 Aluminum Alloy	3.25E-08	3.0769E7
6061-T6 Aluminum Alloy	4.099E-08	2.4938E7
Yellow Brass (35% zinc)	6.4E-08	1.5625E7
Phosphor Bronze (5% tin)	1.1E-07	9.0909E6
Stainless Steel type 302	7.1999E-07	1.3889E6

The effect of using different element materials in antenna construction and analysis of results will be studied in Chapter 4.

3.4.1.3 Element Spacing

Element spacing in array designs is one of the most important issues since it is one of the main factors that change the antenna characteristics. Because the array antenna analyzed for PCL systems is theoretically a phased array antenna, element spacing considerations can be studied using phased array antenna theory.

A most significant concern regarding element spacing is the *grating lobe*, which is described as "additional major lobes that rise to intensity equal to that of the main lobe" [26]. These grating lobes are undesirable since they will cause

major ambiguities in the reception. According to [28], the maximum acceptable element spacing to avoid grating lobes is given as:

$$d_{\max} = \frac{\lambda}{1+\sin\theta_0} \qquad (14)$$

where, d_{max} = maximum acceptable element spacing,

λ = wavelength,

θ_0 = maximum desired look angle.

Using this equation, it is possible to calculate the maximum acceptable element spacing for different desired look angles, which are the angles off boresight that the threat is expected. For example:

$\theta_0 = 90^{\circ} \quad \Rightarrow \quad d_{max} = 0.50\lambda$

$\theta_0 = 60^{\circ} \quad \Rightarrow \quad d_{max} = 0.54\lambda$

$\theta_0 = 30^{\circ} \quad \Rightarrow \quad d_{max} = 0.67\lambda$

Analysis of different element spacings is discussed in detail in Chapter 4.

3.4.1.4 Sub Arrays of Parasitic Elements

Sub Arrays of Parasitic Elements can be used in array antenna designs to increase the gain and directivity. Since the wires have bi-directional or omni-directional pattern, "not only it is feasible to use parasitic and phasing techniques to create directional antennas from the basic omni-directional types, but it is also possible to enhance the initial bi-directivity of other shapes to create quite effective uni-directional arrays" [25].

Since antenna gain is a crucial parameter for an antenna requirement in a PCL system, using parasitic elements in order to increase the gain will be studied for array antenna analysis. These parasitic elements, which will function as directors, will have the same element shape as the driven elements. In Chapter 4, the description of this analysis will be discussed in detail.

3.4.1.5 Media

NECWin Plus enables the program user to simulate the antenna in different media to give more realistic results. There are four basic ground types within the program and they have different characteristics for accelerating both pre-processing and post-processing accuracy. These ground types are:

- No Ground: The antenna is considered to be in free space. In other words, no ground will be included in the calculations. Choice of this type of ground is the best way to compare the antennas that have the same characteristics. Also, this is the fastest calculation method and has the most reliable output data since there is no ground application.

- Perfect Ground: The ground here is assumed to extend infinitely and have infinite conductivity. The code generates an image of the structure reflected in the ground surface. Since perfect ground creates an image antenna identical to the original, it requires twice as long to fill the interaction matrix as a free space model.

- Real Ground: Sometimes called the "fast" or "finite" ground, this option generates an image model modified by the Fresnel plane-wave reflection coefficient approximations for near fields. The precision of this ground type becomes worse as the antenna gets closer to the ground (within several tenths of a wavelength), and it is most appropriate to use this option for relatively compact antenna structures. Choosing this option will make the Real Ground Parameters window appear in NECWin Plus, where you can describe your ground.

- Sommerfeld Ground: The Sommerfeld ground option enables you to more accurately model the ground interaction of the antenna. The NECWin Plus core will process the antenna by using the ground constants calculated using the Sommerfeld-Norton algorithm. Inclusion of these results requires longer processing time, but it significantly improves the accuracy of the model when it is located close to the ground (typically when the antenna is less than 0.1λ above ground). The Sommerfeld (or Sommerfeld-Norton) ground extends indefinitely to the horizon.

In addition, under the Sommerfeld Ground option there are different types of soil conditions, which are available by the selection of values for ground conductivity and relative permittivity (dielectric constant). According to [29], some soil descriptions that are used in antenna modeling are shown in Table 7.

Table 7: Conductivity and Permittivity of Common Ground Conditions

Soil Description	**Conductivity (in S/m)**	**Permittivity (Dielectric Constant)**	**Relative Quality**
Fresh Water	0.001	80	
Salt Water	5.0	81	
Pastoral, low hills, rich soil, typical from Dallas TX to Lincoln NE	0.0303	20	Very Good
Pastoral, low hills, rich soil, typical of OH and IL	0.01	14	Good
Flat country, marshy, densely wooded, typical of LA near the Mississippi River	0.0075	12	
Pastoral, medium hills, and forestation, typical of MD,PA, NY (exclusive of mountains)	0.006	13	
Pastoral, medium hills, and forestation, heavy clay soils, typical of central VA	0.005	13	Average
Rocky soil and steep hills, typically mountainous	0.002	12-14	Poor
Sandy, dry, flat, coastal	0.002	10	
Cities, industrial areas	0.001	5	Very Poor
Cities, heavy industrial areas, high buildings	0.001	3	Extremely Poor

Analysis of using different ground structures on characteristics of array antennas will be studied thoroughly in Chapter 4.

3.4.1.6 Sidelobe Level Reduction Techniques

As discussed in Section 3.3.6.2, Binomial Arrays, Dolph Chebyshev Arrays, and Taylor Arrays will be studied and explored for possible PCL array antenna applications and the results will be evaluated in Chapter 4.

3.4.1.7 Diameter

The American Wire Gauge (AWG) numbers, which correspond to diameters in inches and/or millimeters, are used in antenna construction. These AWG numbers can be used in NECWin Plus as well as any other diameter values. According to [25], common AWG numbers in millimeters are given in Table 8.

Table 8: Common Wire Gauges and Associated Diameters in Millimeters

AWG #	Diameter	AWG #	Diameter	AWG #	Diameter	AWG #	Diameter
1	7.348	*11*	2.305	*21*	0.723	*31*	0.227
2	6.544	*12*	2.053	*22*	0.644	*32*	0.202
3	5.827	*13*	1.828	*23*	0.573	*33*	0.180
4	5.189	*14*	1.628	*24*	0.511	*34*	0.160
5	4.621	*15*	1.450	*25*	0.455	*35*	0.143
6	4.115	*16*	1.291	*26*	0.405	*36*	0.127
7	3.665	*17*	1.150	*27*	0.361	*37*	0.113
8	3.264	*18*	1.024	*28*	0.321	*38*	0.101
9	2.906	*19*	0.912	*29*	0.286	*39*	0.090
10	2.588	*20*	0.812	*30*	0.255	*40*	0.080

Since the antenna elements need to be strong enough to carry the weight of the antenna, the diameter of the wires should be thick enough to handle this weight. In other words, as wavelength increases, so should the diameter of the wires. Therefore, it is preferable to design the wires as thick as possible. However, this tends to increase VSWR values, due to more mutual coupling by an enlarged surface area.

Thus, after studying some examples and considering the experiences of others, I tried several possible diameter values for wire elements. Results and analysis will be shown in Chapter 4.

3.4.2 Objective Functions

The objective functions, which we desire to achieve with any PCL antenna, can be listed as:

- Usable Antenna Pattern
- High Gain
- Low Sidelobe Levels
- Reasonable Size
- Low Voltage Standing Wave Ratio (VSWR)

It would be appropriate to have a closer look at the properties of these objective functions, in order to understand how to interpret them in NECWin Plus.

3.4.2.1 Usable Antenna Pattern

For PCL, the antenna pattern main-beam is preferred to be narrow in order to increase the resolution accuracy. In this thesis research, this goal will be maintained as one of the most important objective functions.

3.4.2.2 High Gain

Just like in all antenna cases, the PCL antenna requires high gain in order to detect distant range threats. However, this range cannot be stipulated since there are many factors involved, such as atmospheric conditions, ground specifications, transmission lines in the antenna, object size, etc. Nevertheless, for this research, a minimum of 15dB gain is desired as a goal since there will be some unexpected losses.

3.4.2.3 Low Sidelobe Levels

A uniform array antenna (identical elements with the identical amplitudes) will bring about –13dB sidelobe level. Yet, it is advantageous to have lower sidelobe levels than –13dB for a PCL. Therefore, sidelobe reduction techniques, i.e. Binomial, Dolph Chebyshev and Taylor, will achieve this objective function to some degree.

3.4.2.4 Reasonable Size

PCL antennas should be operated covertly in order not to be detected by enemy forces. However, using FM signals means that the wavelength will be around three meters, which will correspondingly result in long antenna elements. Using multiple elements in the array design will bring about a large antenna design, which is contrary to covert operations. Therefore, designing a

small PCL antenna, yet big enough to function efficiently, is an objective function for this thesis.

3.4.2.5 Low Voltage Standing Wave Ratio (WSVR)

"VSWR indicates the amount of interference between the two opposite traveling waves; the smaller the VSWR value, the lesser the interference. VSWR has values in the range of 1 ≤ VSWR ≤ ∞, and is given by" [30].

$$VSWR = \frac{|E_0^+| + |E_0^-|}{|E_0^+| - |E_0^-|} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{15}$$

where, E_0^+ = amplitude of the positive traveling wave,

E_0^- = amplitude of the negative traveling wave,

Γ = reflection coefficient.

"For many applications, low VSWR is a luxury and not a necessity" [26]. However, for this research, low VSWR values are desirable since the array antenna for a PCL system should be realistic, convenient, and practical. According to [26], the relation between VSWR and transmitted power for a mismatched antenna is given in Table 9 as:

Table 9: VSWR and Power Relation for a Mismatched Antenna

VSWR	Percentage of Reflected Power	Percentage of Transmitted Power
1.0	0.0%	100%
1.1	0.2%	99.8%
1.2	0.8%	99.2%
1.5	4.0%	96.0%
2.0	11.1%	88.9%
3.0	25.0%	75.0%
4.0	36.0%	64.0%
5.0	44.4%	55.6%
5.83	50.0%	50.0%
10.0	66.9%	33.1%

In order to achieve low VSWR (that is close to '1') there are some factors to consider while modeling the antenna in NECWin Plus. Optimizing the element spacing, element diameter, and parasitic element utilization, etc.- are a key to achieve low VSWR values.

3.5 Potential Array Antenna Configurations for PCL Systems

3.5.1 Determination of Potential Array Antenna Configurations

After evaluating and studying several variables to achieve objective functions, some array design configurations, which can be possible for a PCL system, will be introduced. The decision for the best potential array antenna will be given considering the results of variable effects on desirable objective functions. Analysis of this array structure will be studied and output data will be shown in Chapter 4.

3.5.2 Applying Potential PCL Array Antennas to DOA Estimators

3.5.2.1 DOA Estimators

In this research, the potential array antennas will be applied to different DOA estimators, which are the MATLAB simulation tools generated and modified by Ozcetin in his thesis [13], in order to analyze and compare the results. These DOA estimation techniques are:

- Conventional Beam Forming (CBF)
- Multiple Signal Characterization (MUSIC)
- Analytical Constant Modulus Algorithm (ACMA)

3.5.2.2 Test Criteria

There will be two random objects in the free space with no range information and with zero elevation. One of the objects will be fixed at +5 degrees off boresight of the antenna, whereas the other object will be moving from –5 degrees to +15 degrees off boresight. This approach will help to have a better understanding of the resolution characteristics of the each antenna.

In order to have accurate measurements, MATLAB simulations will have 400 runs and there will be 100 samples taken from antenna elements. This procedure, which is a common statistical analysis method, will prevent having incorrect results.

Application of the array antennas to these DOA estimators and the results of them will be shown and compared in Chapter 4.

3.6 Beam Steering Theorem

The main beam of a phased array antenna is steered by individually controlling the phase of the waves transmitted and received by each element. According to [28], for the transmitter case, the phase difference needed to steer the beam is given by:

$$\Delta\phi = 2\pi \frac{d \sin\theta}{\lambda} \qquad (16)$$

where, $\Delta\phi$ = element-to-element phase difference,

d = distance between the elements,

θ = angle off boresight,

λ = wavelength.

This equation is also valid for the receiver case due to the reciprocity theorem; except the fact that phase difference is caused by the incident wave coming from angle θ.

Array beam steering results in:

- Decrease in the total gain of the array,
- Increase in the VSWR values due to multiple reflection among the elements within the array,

- Wider main beam.

Increasing the maximum look angle or steering angle (θ) will make these conditions worse due to increased mutual coupling. Results of a 16-element array shown in Figure 17 through Figure 24 will be helpful to have a better understanding of this concept. Figure 17 – Figure 20 show the radiation pattern of the same array with different look angles. Figure 21 – Figure 24 show the VSWR values of the same arrays, respectively.

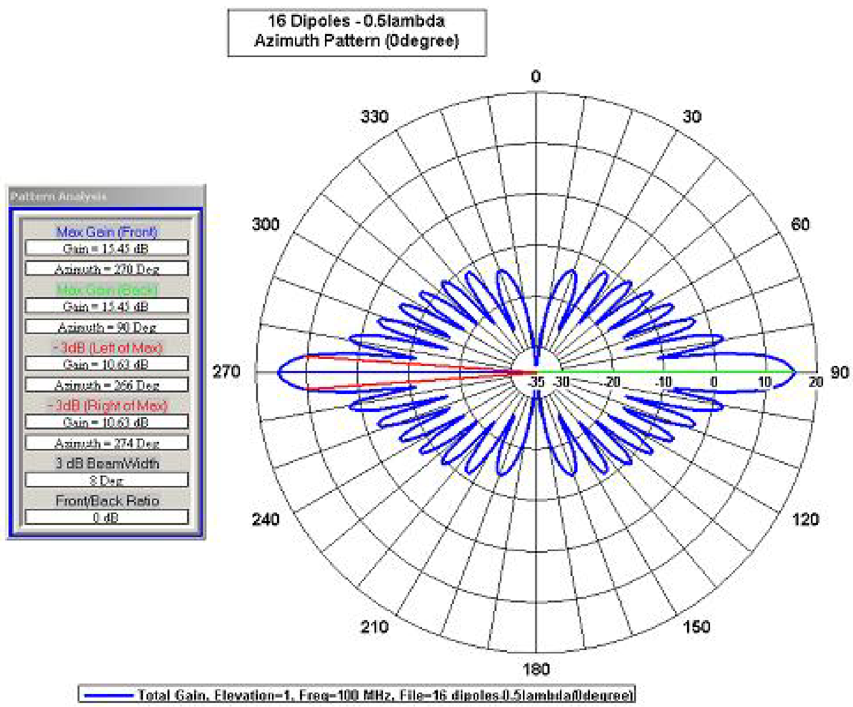

Figure 17: Azimuth Pattern at 0-Degree Look Angle

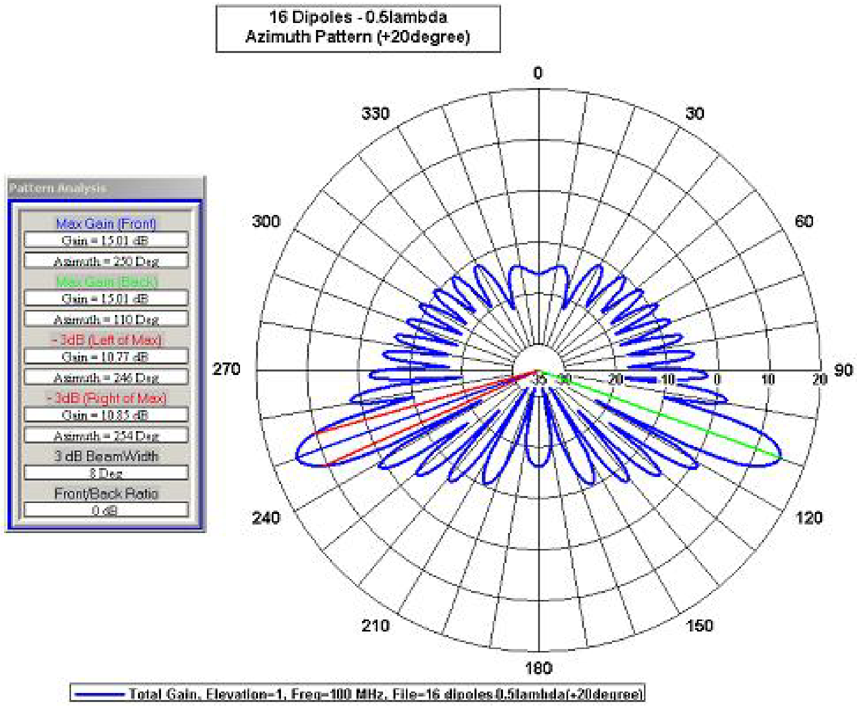

Figure 18: Azimuth Pattern at 20-Degree Look Angle

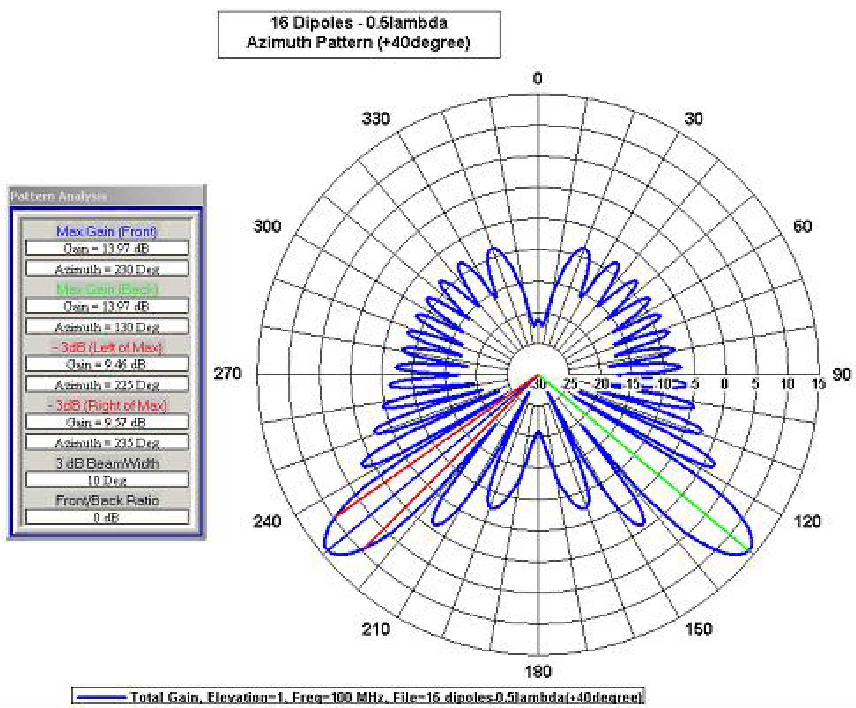

Figure 19: Azimuth Pattern at 40-Degree Look Angle

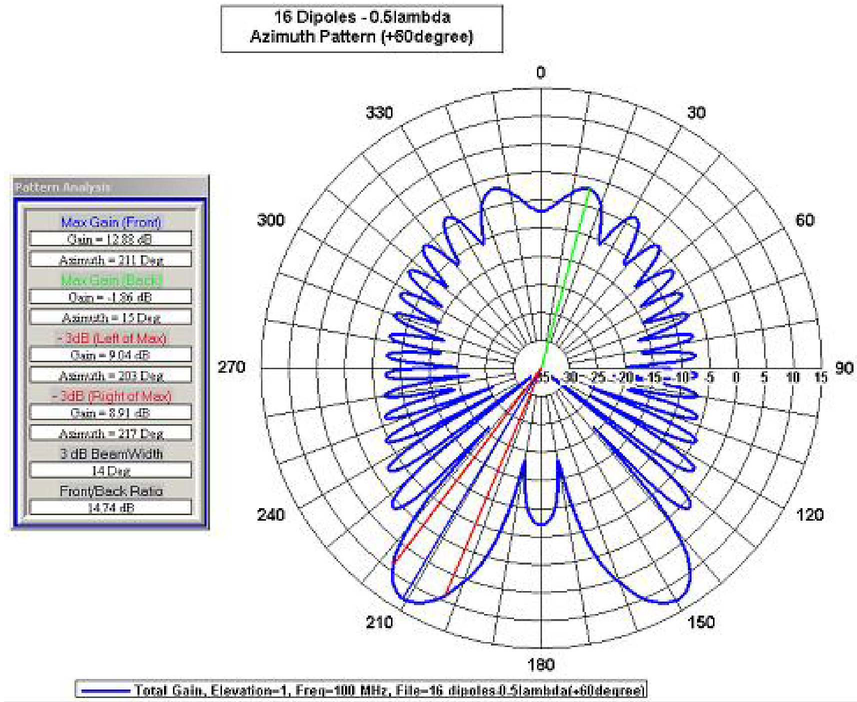

Figure 20: Azimuth Pattern at 60-Degree Look Angle

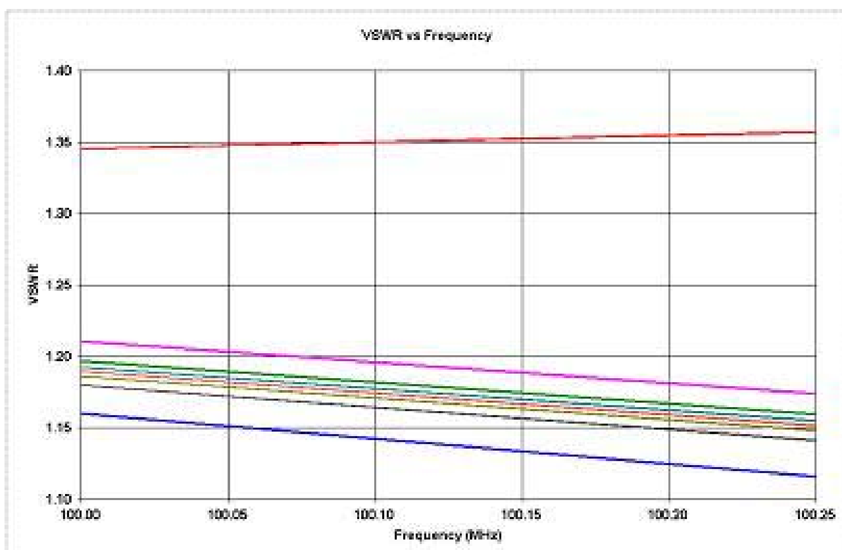

Figure 21: VSWR Values at 0-Degree Look Angle

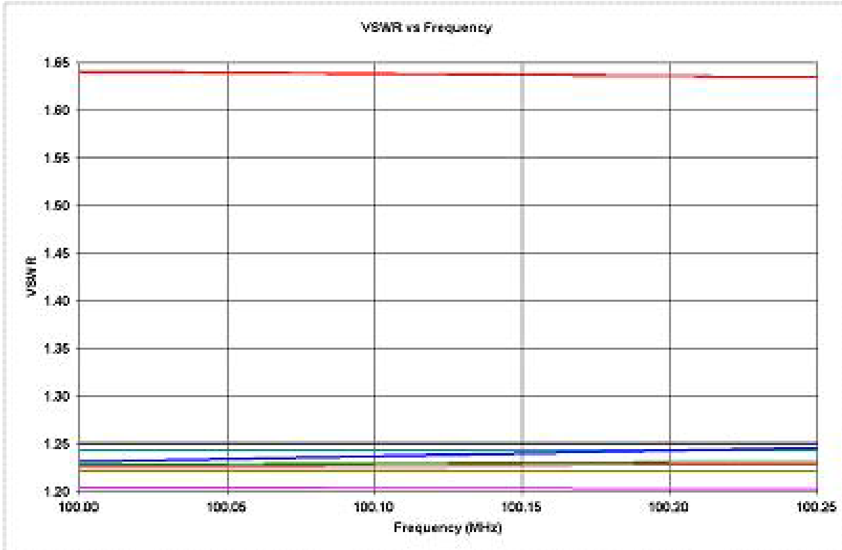

Figure 22: VSWR Values at 20-Degree Look Angle

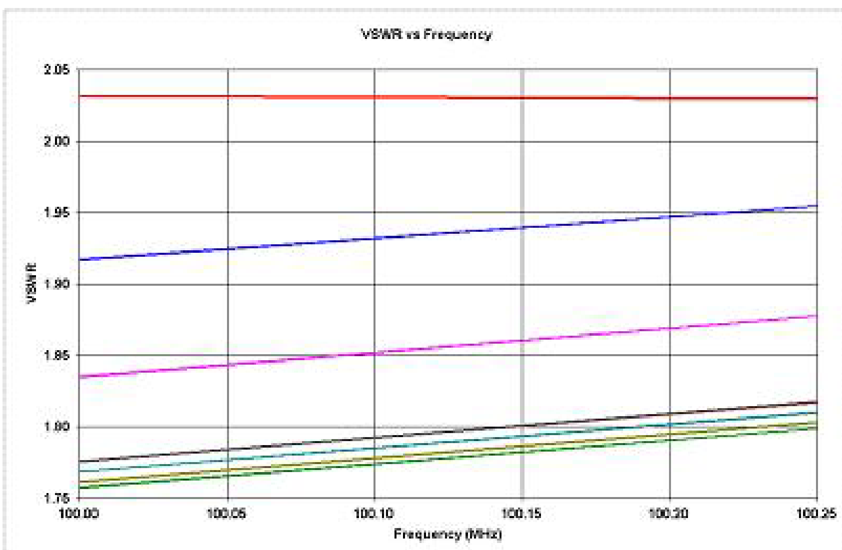

Figure 23: VSWR Values at 40-Degree Look Angle

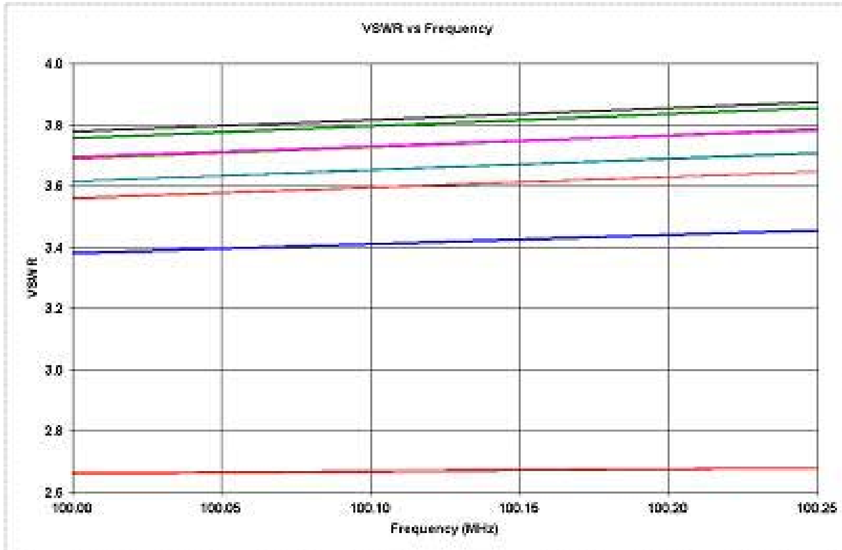

Figure 24: VSWR Values at 60-Degree Look Angle

This study and the output of this phased array will be analyzed by applying it to the potential array designs for PCL systems next, in Chapter 4.

Chapter 4 - RESULTS AND ANALYSIS

In this chapter, different configurations of array antennas will be simulated and analyzed by using NECWin Plus. Results will be displayed and evaluated for the PCL systems.

4.1 Preset Parameters

Since there are many variables to adjust within NECWin Plus, there will be some fixed starting parameters to entirely compare and analyze antenna designs. These preset parameters are chosen as:

- Frequency Specification: Since the required bandwidth of the antenna is 88MHz through 108MHz, 100MHz is chosen for the starting frequency. This frequency is almost in the middle of bandwidth and will allow more straightforward computations.

- Element Material: Perfect conductors will be the fixed element material since it allows more precise comparisons among the antenna designs and makes NECWin Plus run time shorter. (Exception: Different element materials will be attempted when analyzing element materials.)

- Element Spacing: Element spacings will be 0.5λ in NECWin Plus computations for analysis of array antennas, since it gives the maximum desired look angle value. (Exception: Different element spacings will be studied when analyzing element spacing differentiations).

- Sources: Equal current sources with amplitude of 1 Ampere (as suggested in [25]) will be applied to each element as a preset parameter. (Exception: Different amplitudes of sources will be attempted when analyzing sidelobe level reduction techniques.)

- Media: "Choice of *free space* or *no-ground* is often the best for comparison of antennas of similar types. Moreover, it usually provides the most rapid calculation speeds and yields the highest accuracy output data" [25]. Therefore, free space is chosen as the preset media. (Exception: Different ground structures will be attempted when analyzing ground effects.)

- Wire Diameter: Wire diameter will be 0.5mm since its width is thick enough to carry its weight, and thin enough to decrease the VSWR value of the array structure. (Exception: Different wire diameters will be studied when analyzing diameter effects.)

- Characteristic Impedance of the Elements: "Since many dipoles are operated with 50Ω coaxial cable, establishing a 50Ω characteristic impedance is a common practice" [25]. Characteristic impedance of 50Ω will be used in entire analysis.

- Incoming (Incident) Wave: Since the array elements will be aligned on the X-axis, the incident wave is assumed as coming from the negative Y-axis. The basic geometry of this concept is shown in Figure 25.

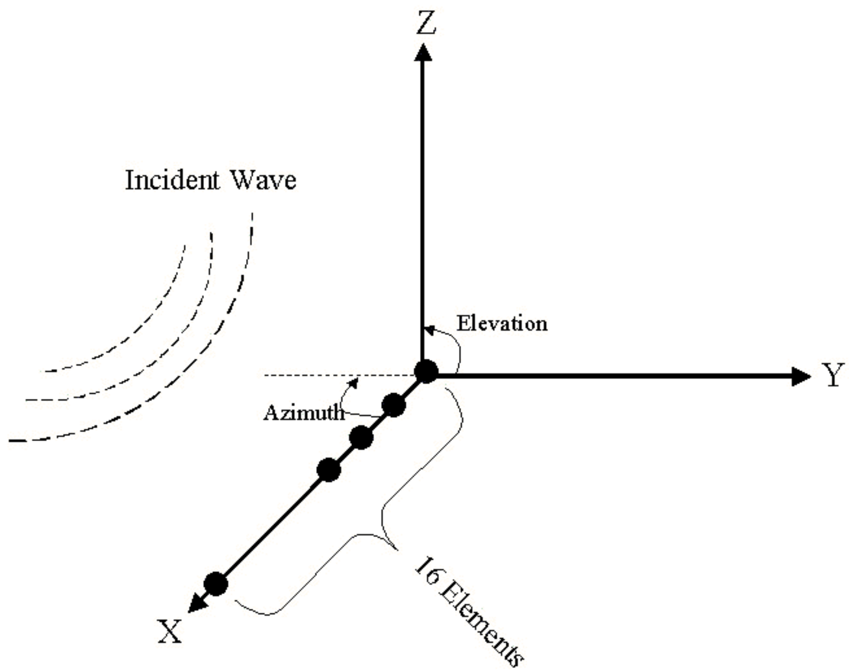

Figure 25: Basic Geometry of Array Antenna in Cartesian Coordinates

4.2 Analysis and Results

As stated in Section 3.4, effects of changing variables on the objective functions will be shown and evaluated in this section.

4.2.1 Element Shapes

There are six basic structures that will be analyzed for this thesis. Some features of these wire elements are shown below:

Dipoles:

- Elements are approximately $\lambda/2$ (±0.05meters) long,
- Vertically aligned (for vertical polarization),

- Sources are in the middle of each wire.

Sleeve Dipoles-x:

- Fed elements are approximately $\lambda/2$ (±0.05meters) long,
- Parasitic elements are $\lambda/10$ long, $\lambda/10$ away from fed elements, and they are on the X-axis.
- Vertically aligned (for vertical polarization),
- Sources are in the middle of each fed wire.

Sleeve Dipoles-y:

- Fed elements are approximately $\lambda/2$ (±0.05meters) long,
- Parasitic elements are $\lambda/10$ long, $\lambda/10$ away from fed elements, and they are on the Y-axis.
- Vertically aligned (for vertical polarization),
- Sources are in the middle of each fed wire.

Square Loops-v:

- Each side of the loops is approximately $\lambda/4$ (±0.05meters) long,
- Vertically Polarized,
- Sources are in the middle of each left side of the loops.

Square Loops-h:

- Each side of the loops is approximately $\lambda/4$ (±0.05meters) long,

- Horizontally Polarized (for comparison with other structures),
- Sources are in the middle of each lower side of the loops.

Diamonds:

- Elements are approximately λ/4 (±0.05meters) long,
- Both horizontally and vertically (linearly) polarized,
- Sources are in the lower corner of each diamond.

Figures 26-31, basic configurations and geometries of these elements are shown and magnitudes of current distributions are displayed.

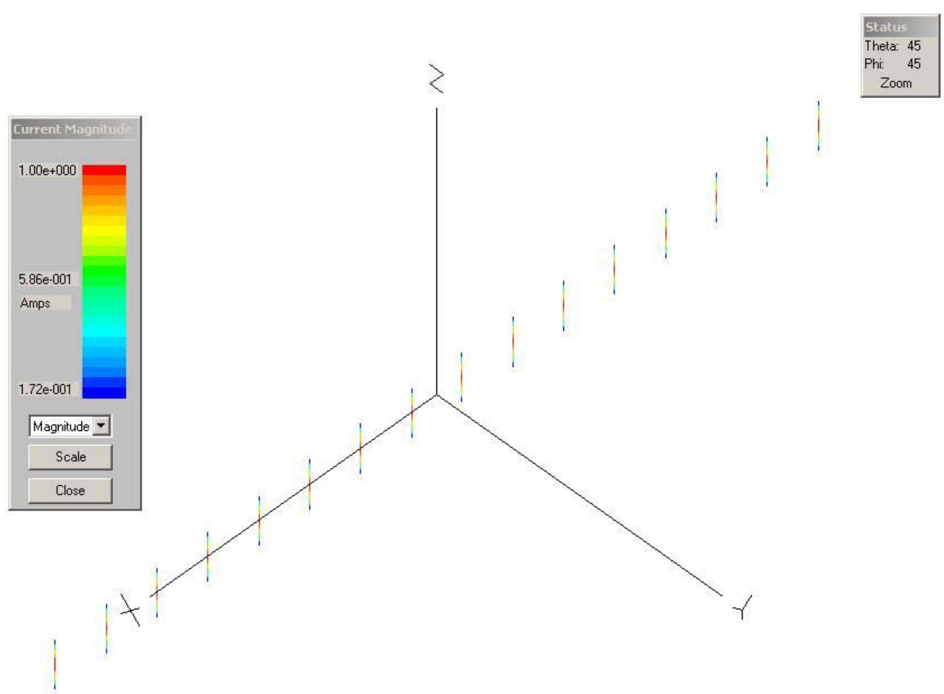

Figure 26: Basic Geometry of the Elements (Dipoles)

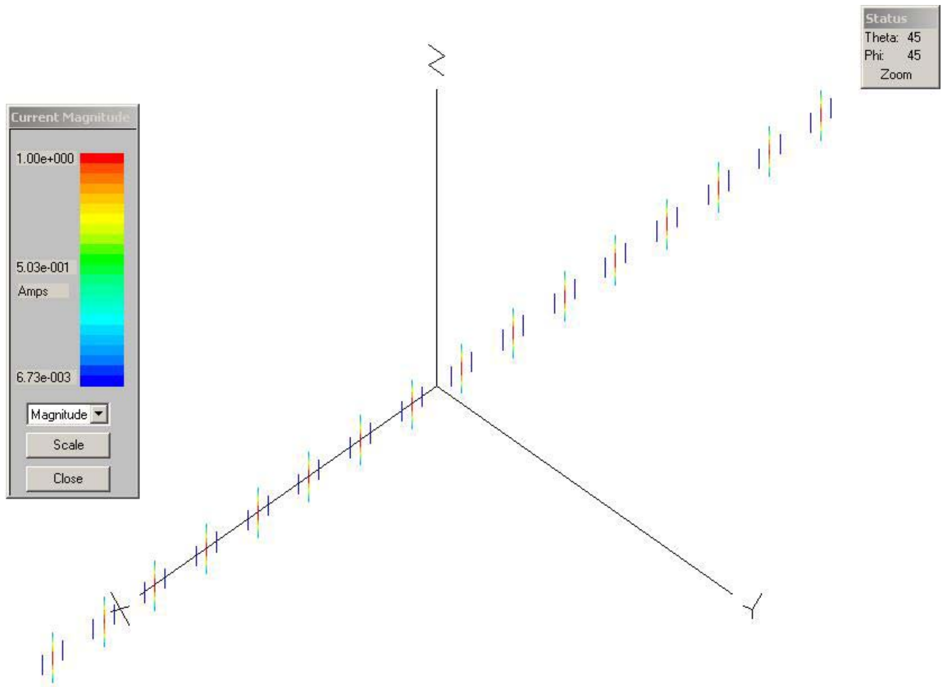

Figure 27: Basic Geometry of the Elements (Sleeve Dipoles-x)

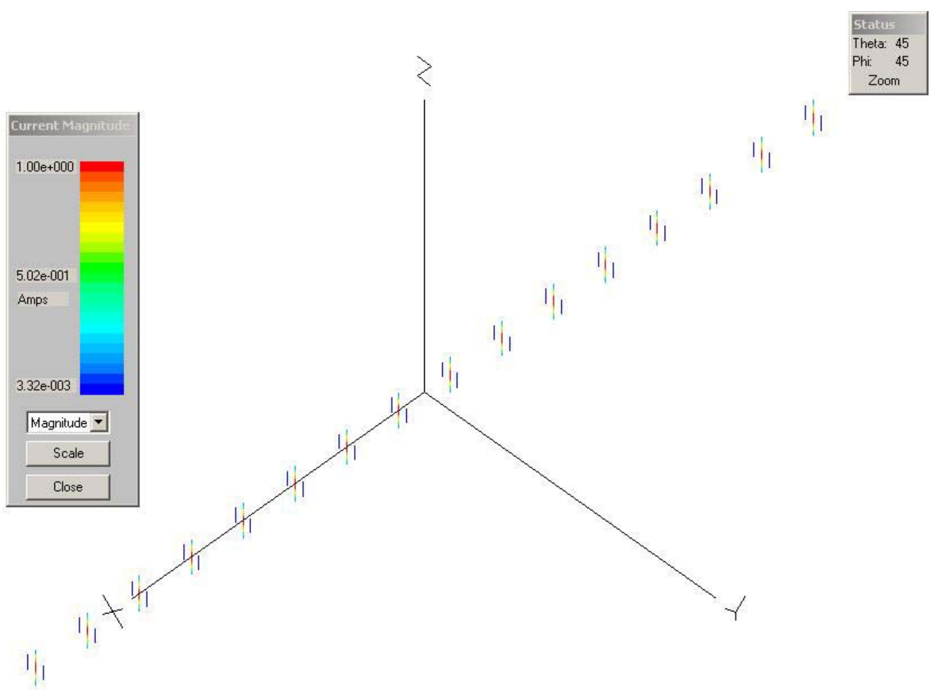

Figure 28: Basic Geometry of the Elements (Sleeve Dipoles-y)

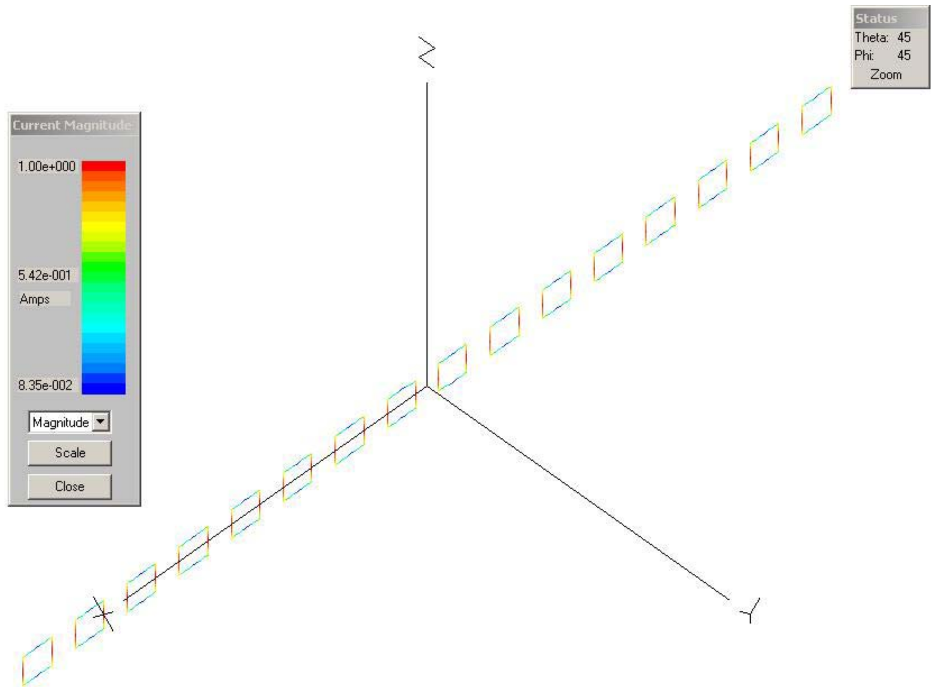

Figure 29: Basic Geometry of the Elements (Square Loops-v)

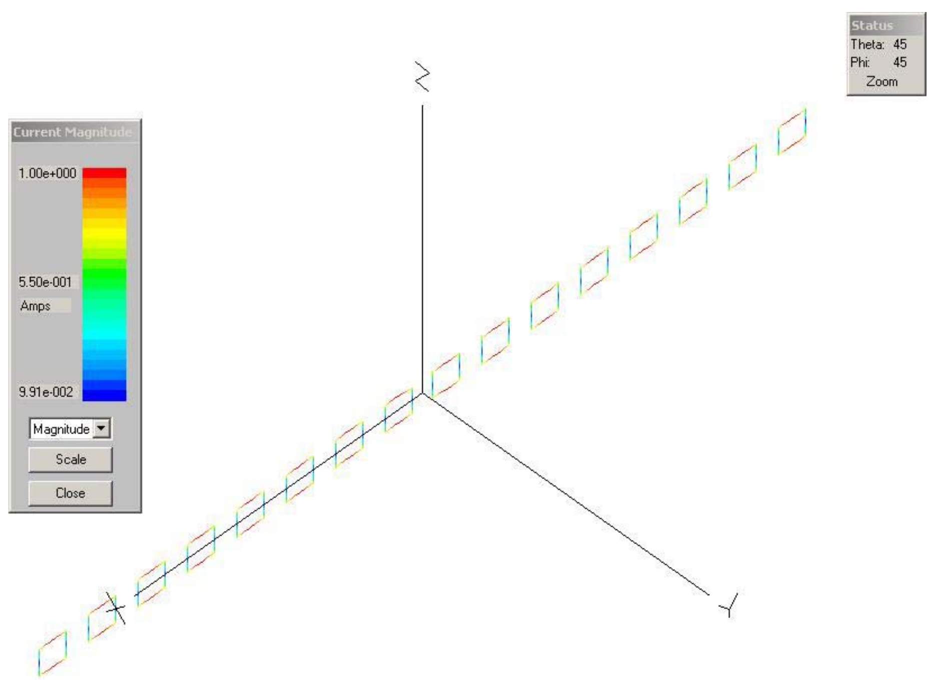

Figure 30: Basic Geometry of the Elements (Square Loops-h)

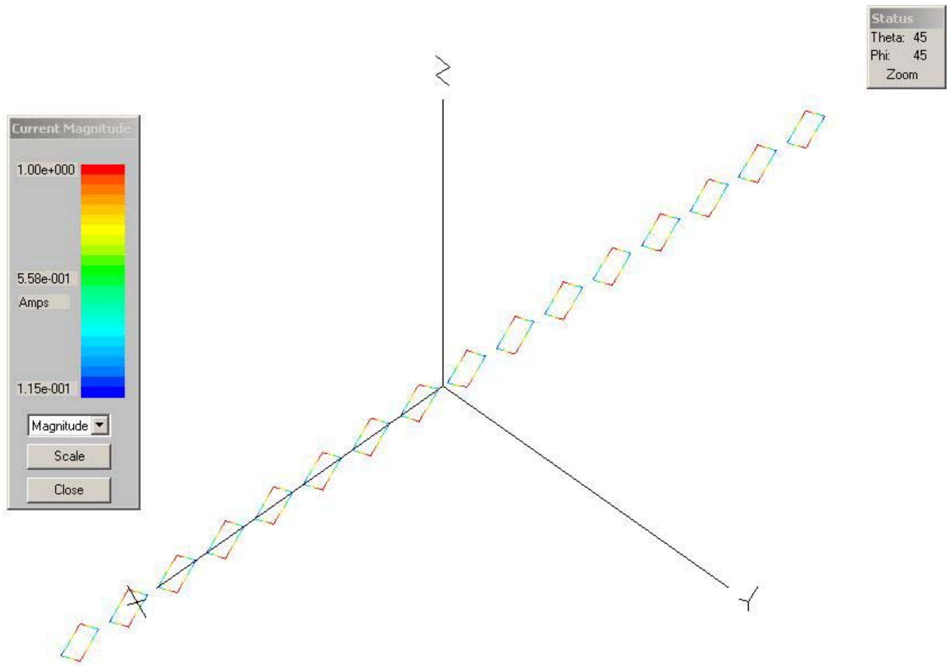

Figure 31: Basic Geometry of the Elements (Diamonds)

In Figures 32-37, the azimuth patterns of these elements are shown, where in Figures 38-43 VSWR values of different elements are shown in rectangular plot format: respectively:

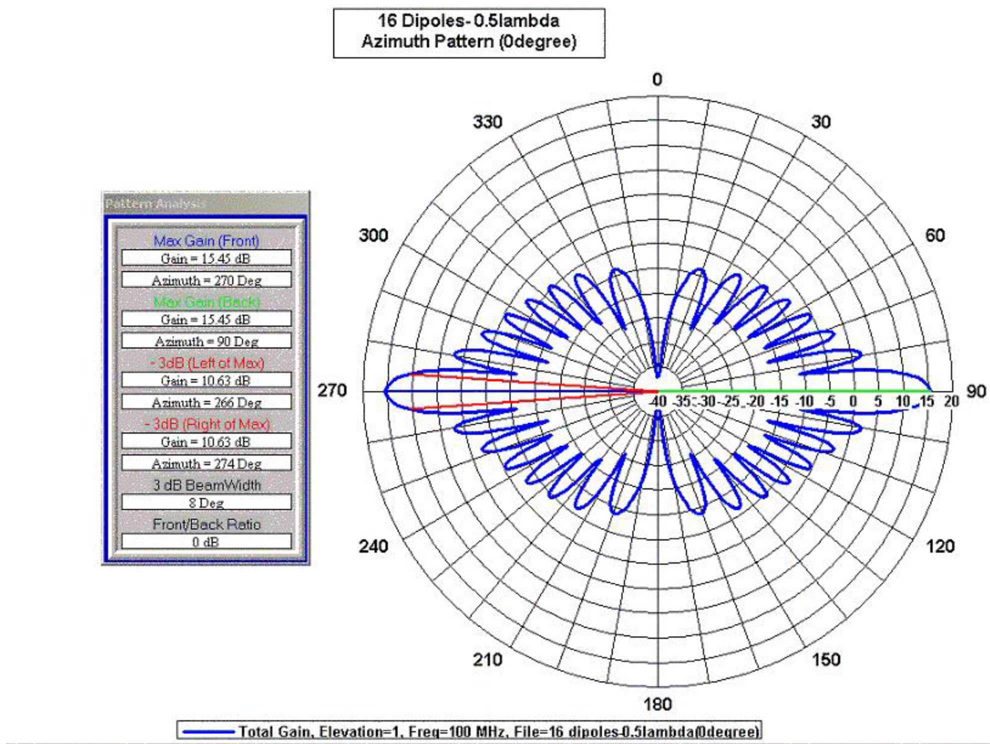

Figure 32: Azimuth Pattern of Different Elements (Dipoles)

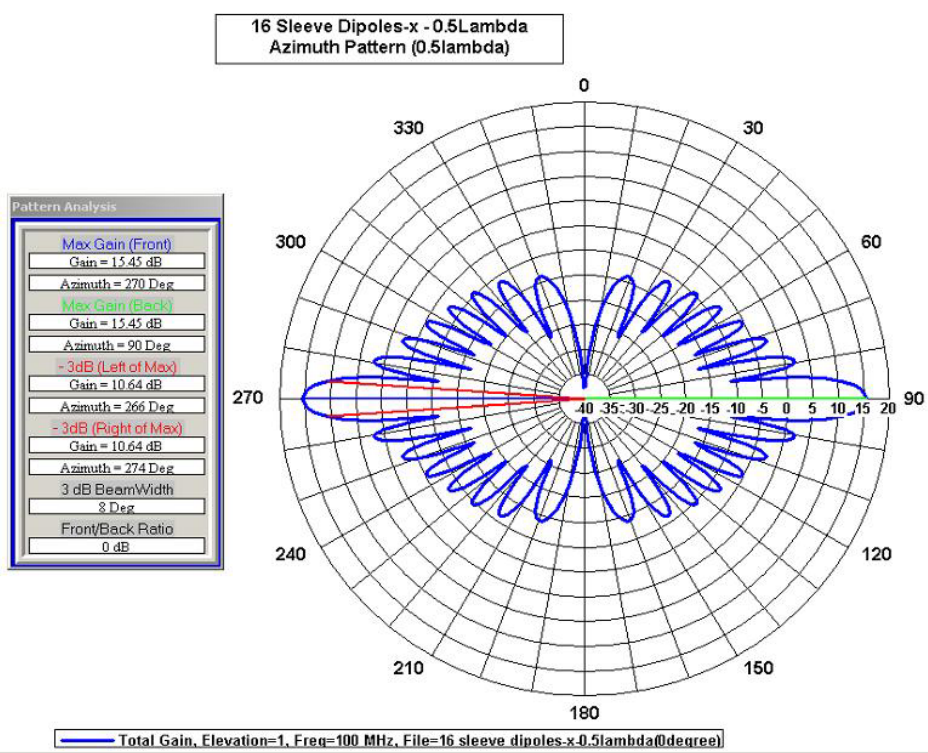

Figure 33: Azimuth Pattern of Different Elements (Sleeve Dipoles-x)

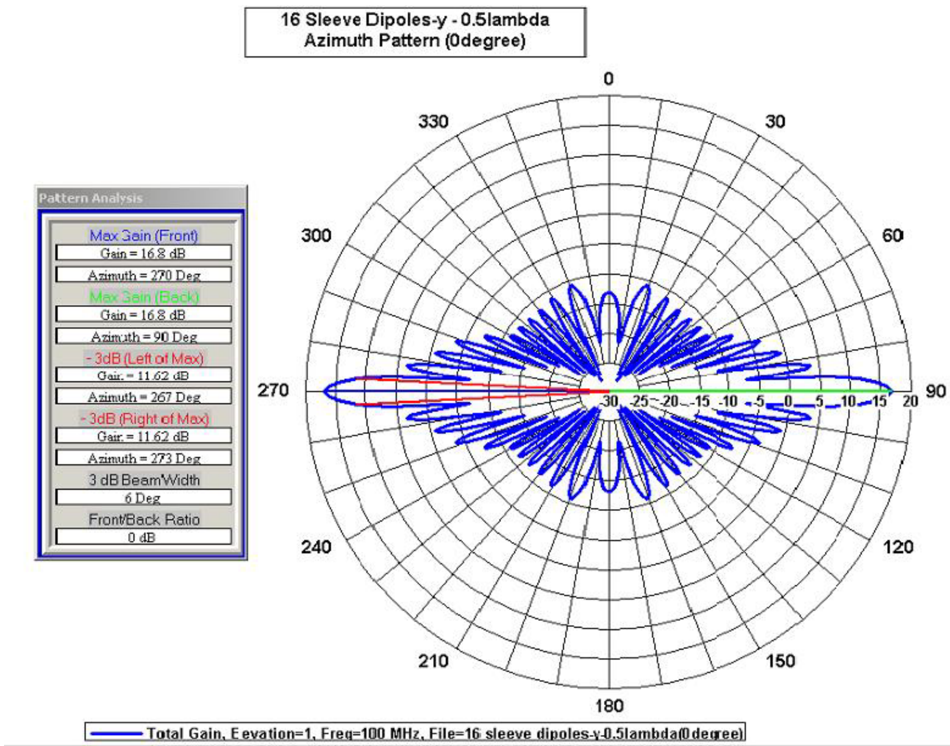

Figure 34: Azimuth Pattern of Different Elements (Sleeve Dipoles-y)

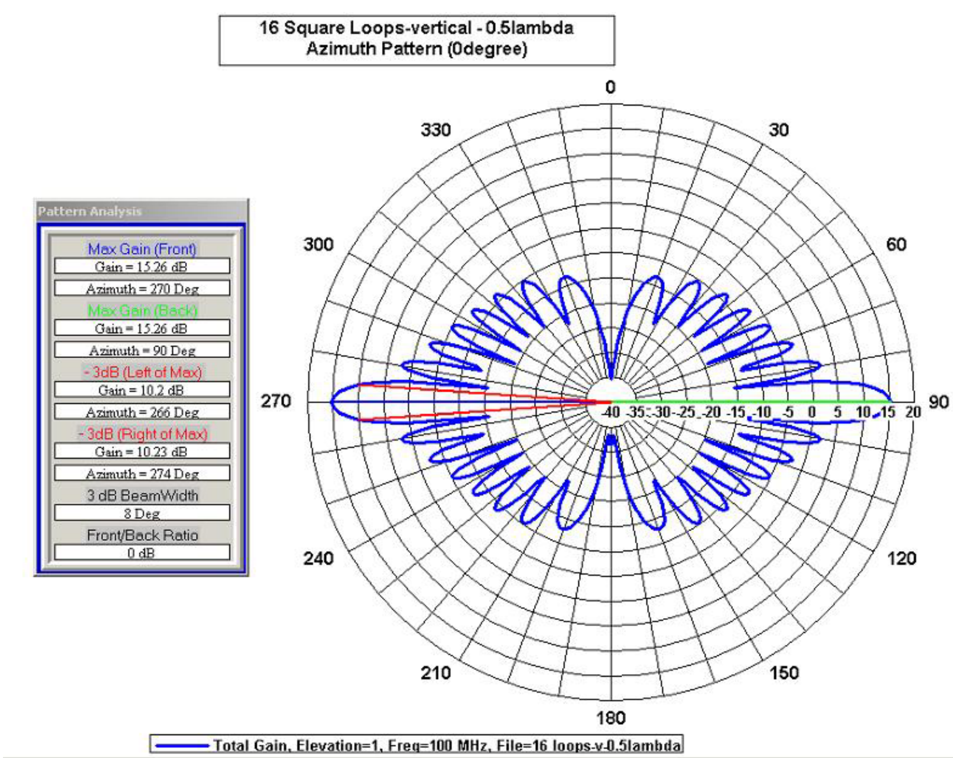

Figure 35: Azimuth Pattern of Different Elements (Square Loops–v)

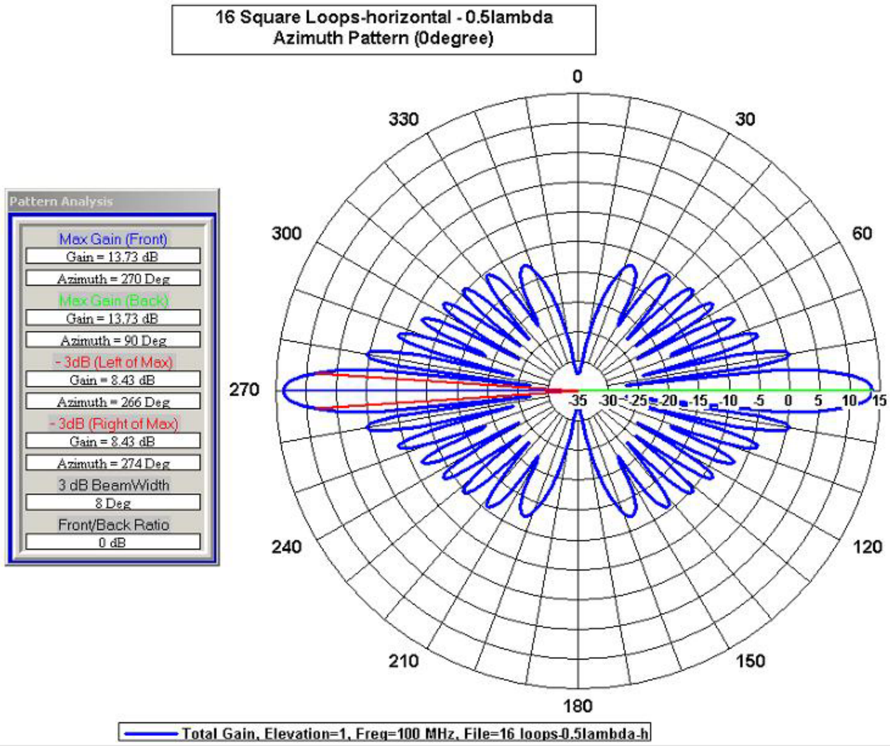

Figure 36: Azimuth Pattern of Different Elements (Sleeve Dipoles-x)

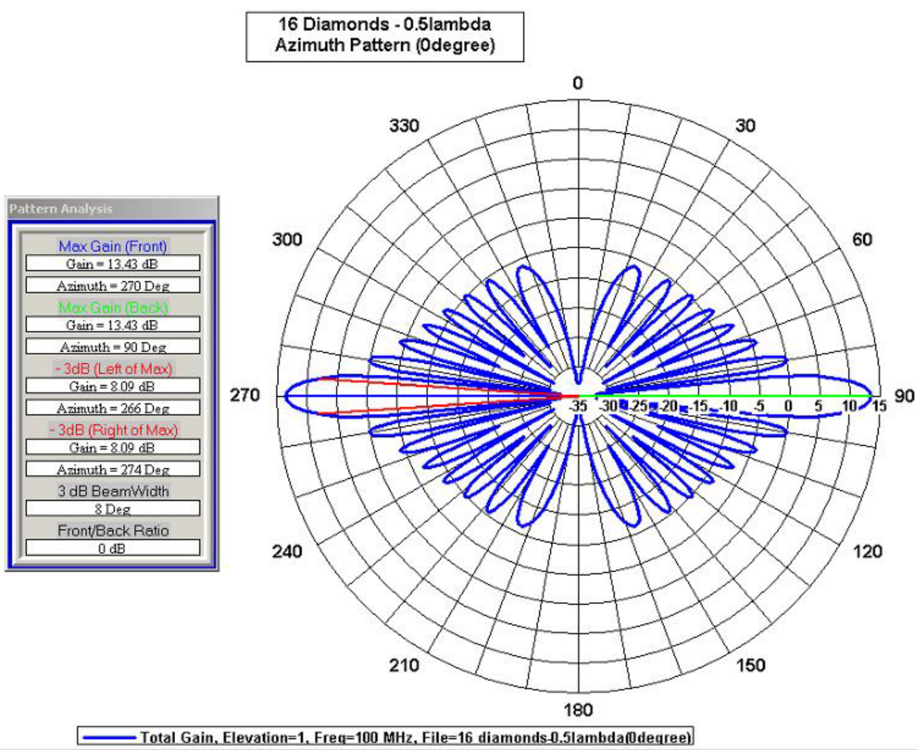

Figure 37: Azimuth Pattern of Different Elements (Diamonds)

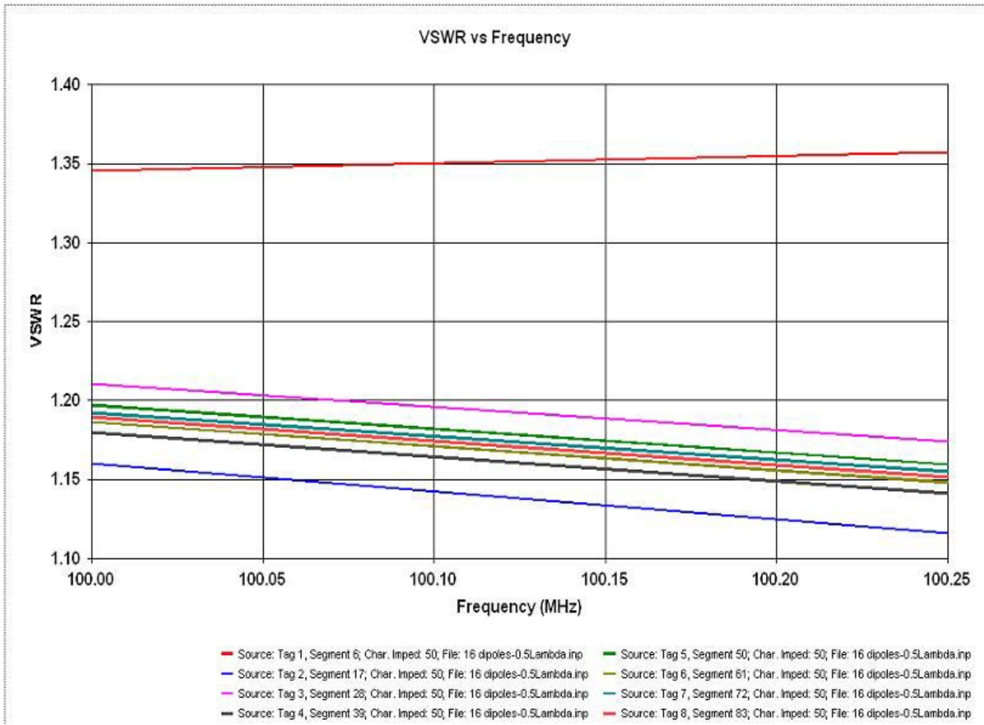

Figure 38: VSWR Values of Different Elements (Dipoles)

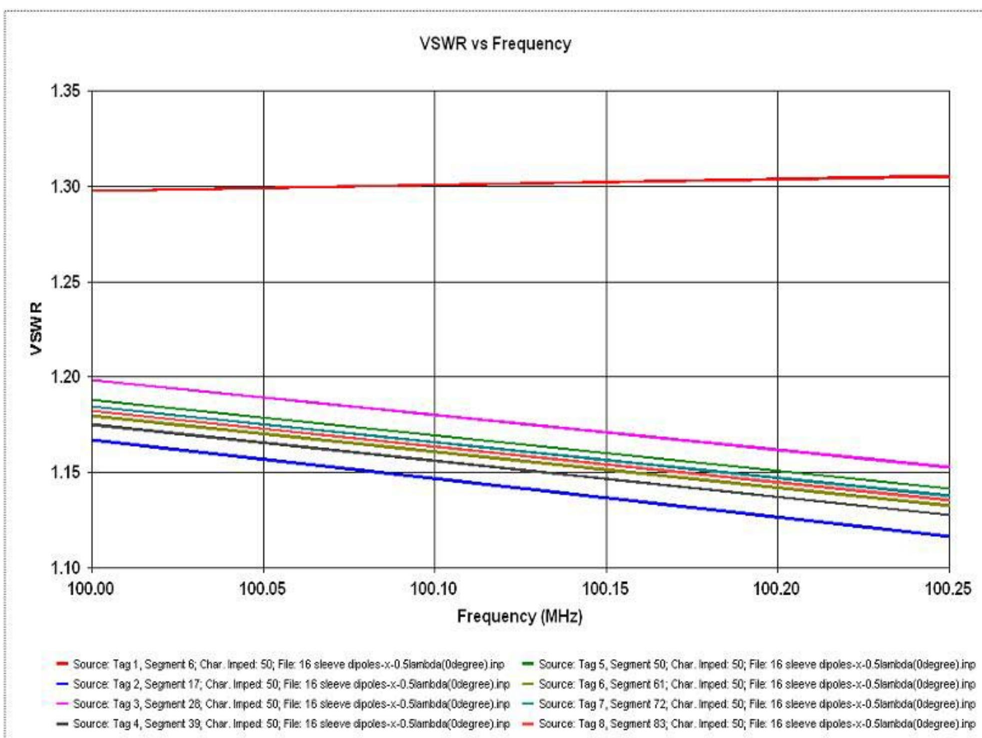

Figure 39: VSWR Values of Different Elements (Sleeve Dipoles-x)

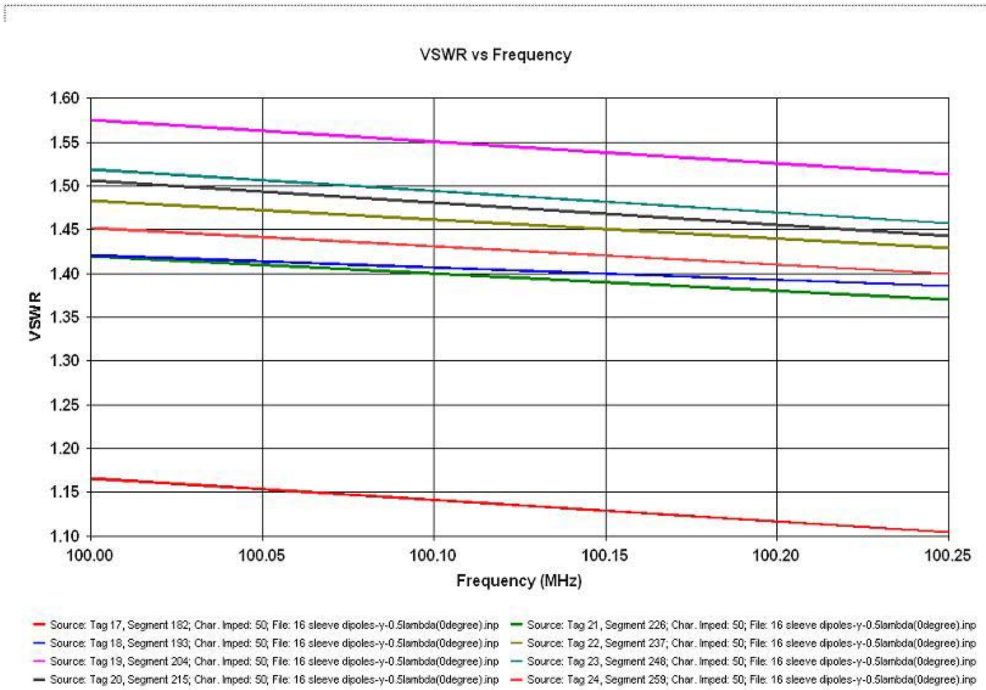

Figure 40: VSWR Values of Different Elements (Sleeve Dipoles-y)

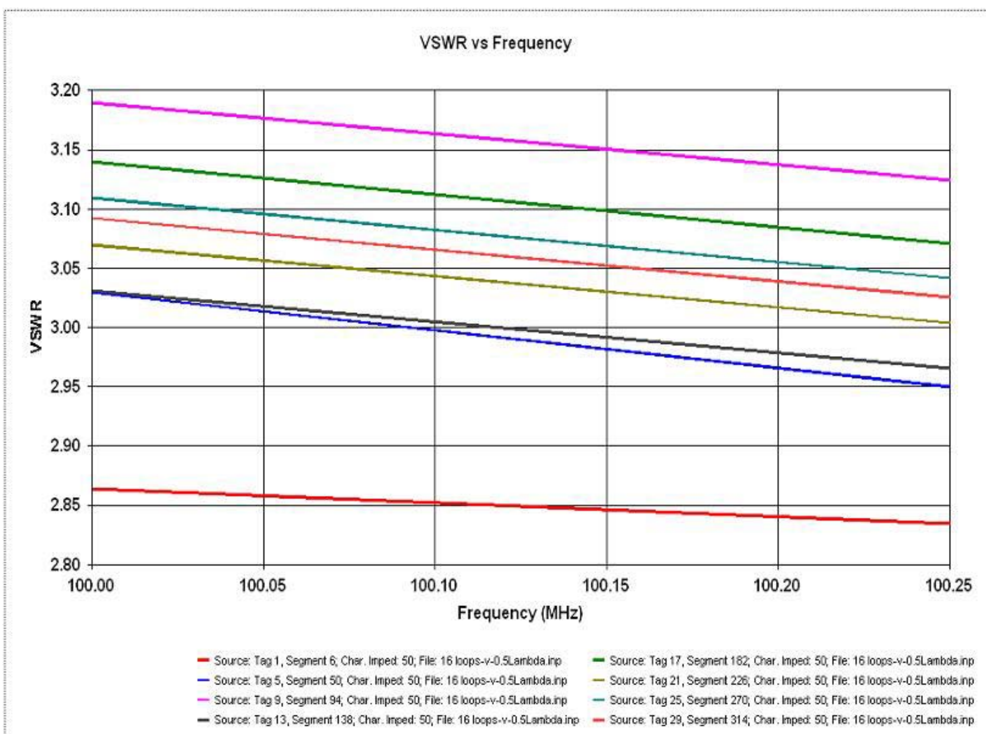

Figure 41: VSWR Values of Different Elements (Square Loops-v)

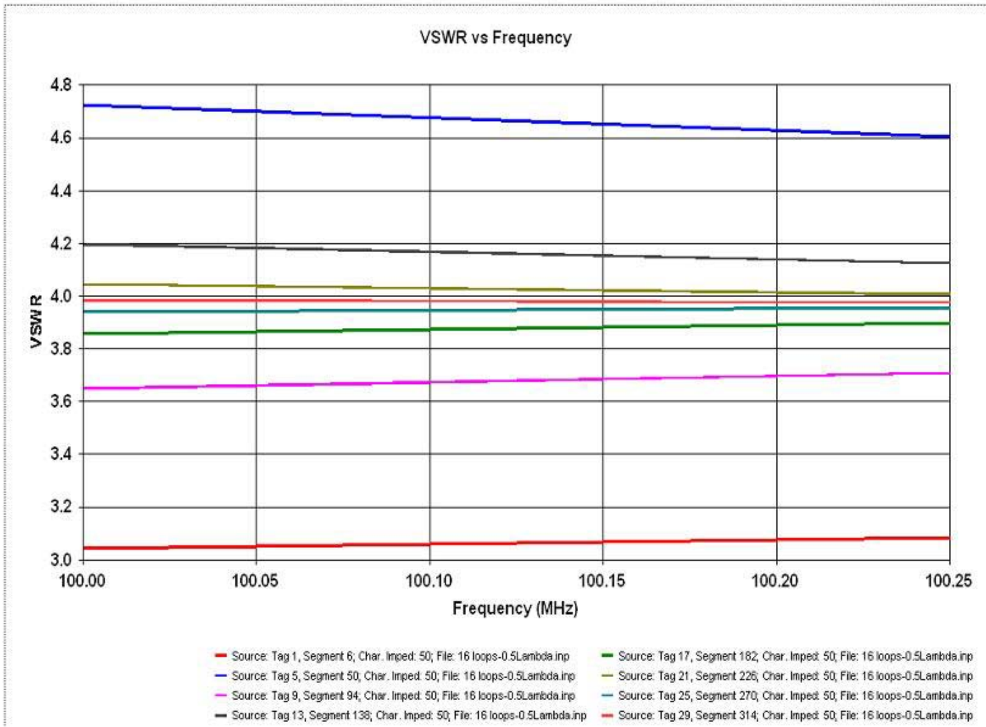

Figure 42: VSWR Values of Different Elements (Square Loops-h)

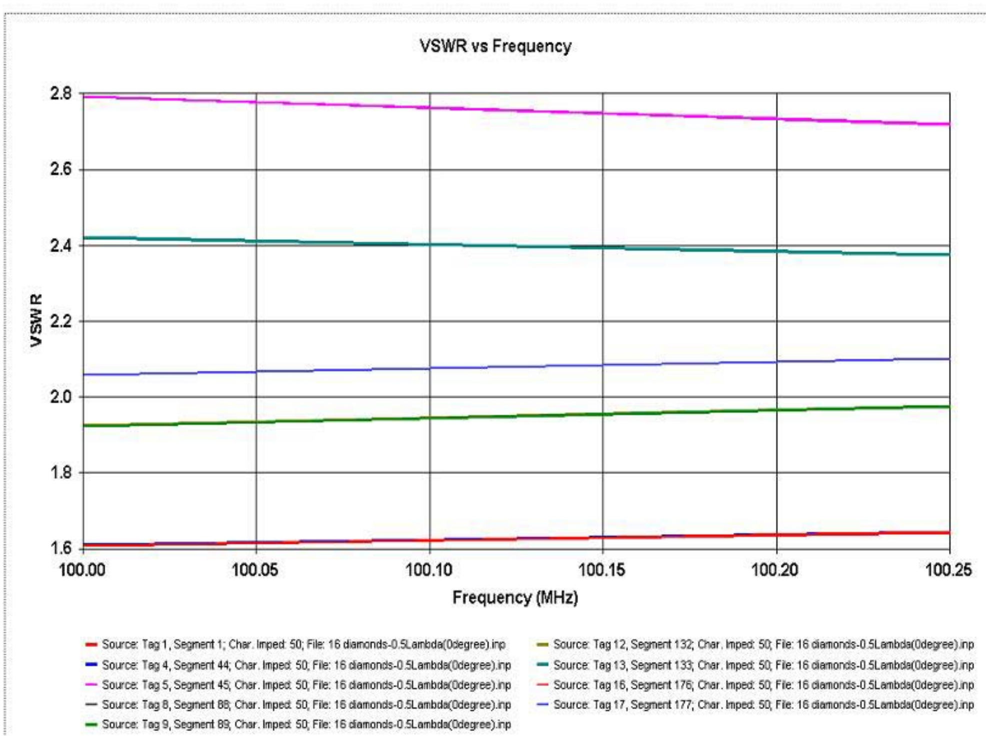

Figure 43: VSWR Values of Different Elements (Diamonds)

Observations:

- All element shapes have the same characteristics of radiation patterns with slight differences in total gains.
- Sleeve Dipoles appear to have the maximum gain.
- VSWR value increases with the complexity of the elements (from dipoles to diamonds). Dipoles and x-oriented sleeve dipoles have the minimum VSWR values.
- Arrays with the dipoles have the minimal size for covert operation.
- Dipoles might be the most advantageous element design since they are simple, cheap, and as effective as the others.

4.2.2 Element Material

According to Table 6 and the information given in Section 3.4.1.2, there are several materials that can be used in element designs for antennas. But for analysis, the best scenario (perfect conductor), most common scenario (pure aluminum), and worst scenario (stainless steel) will be compared and analyzed.

The radiation pattern for each element material is sketched in Figure 44.

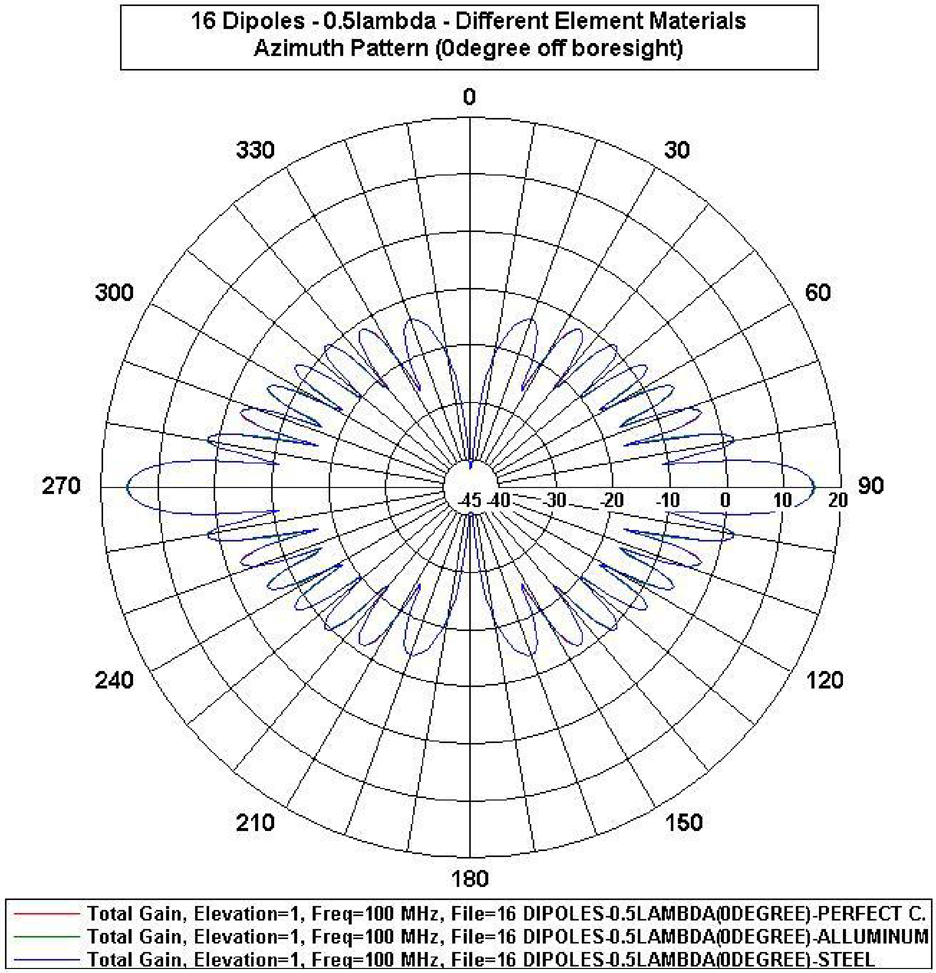

Figure 44: Azimuth Patterns of Arrays of Elements with Different Material

In table 10, the results of using different materials in elements are given as:

Table 10: Effects of Using Different Element Materials

	Perfect Conductor	*Aluminum*	*Stainless Steel*
VSWR Range	1.3456 – 1.1599	1.3492 – 1.1578	1.365 – 1.1507
Efficiency	100%	99.72%	98.54%

Observations:

- Utilization of different element materials such as aluminum or stainless steel has little effect on the radiation pattern.
- A slight increase on the VSWR value occurs, when a material is used with worse permittivity and conductivity values.
- Using a material with worse permittivity and conductivity values decreases the efficiency of the antenna.
- Using pure aluminum can be more advantageous due to cost and efficiency.

4.2.3 Element Spacing

Using the equation for maximum acceptable element spacing to avoid grating lobes, which is found in Section 3.4.1.3, and considering the maximum desired look angle off boresight (θ_0), the optimum spacing between the elements should be:

$$\theta_0 = 90^o \quad \Rightarrow \quad d_{max} = 0.50\lambda,$$

$$\theta_0 = 60^o \quad \Rightarrow \quad d_{max} = 0.54\lambda,$$

$$\theta_0 = 30^o \quad \Rightarrow \quad d_{max} = 0.67\lambda,$$

Bearing this in mind, the element spacing values of 0.45λ, 0.50λ, 0.56λ, and 0.65λ are compared and, the azimuth patterns of 10^o, 20^o, 30^o, and 45^o off boresight angles are compared in Figures 45 – 48.

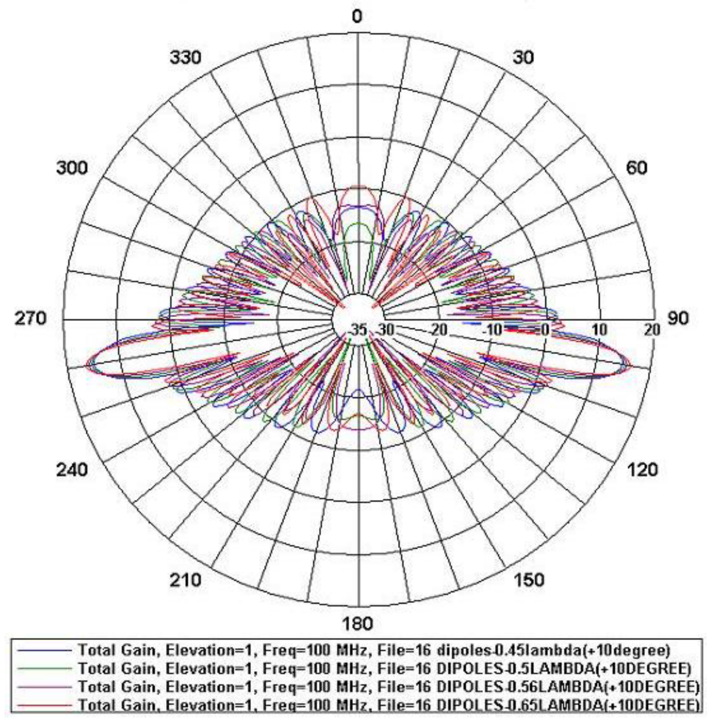

Figure 45: Azimuth Patterns of Arrays with Different Element Spacings
(10 Degrees off Boresight)

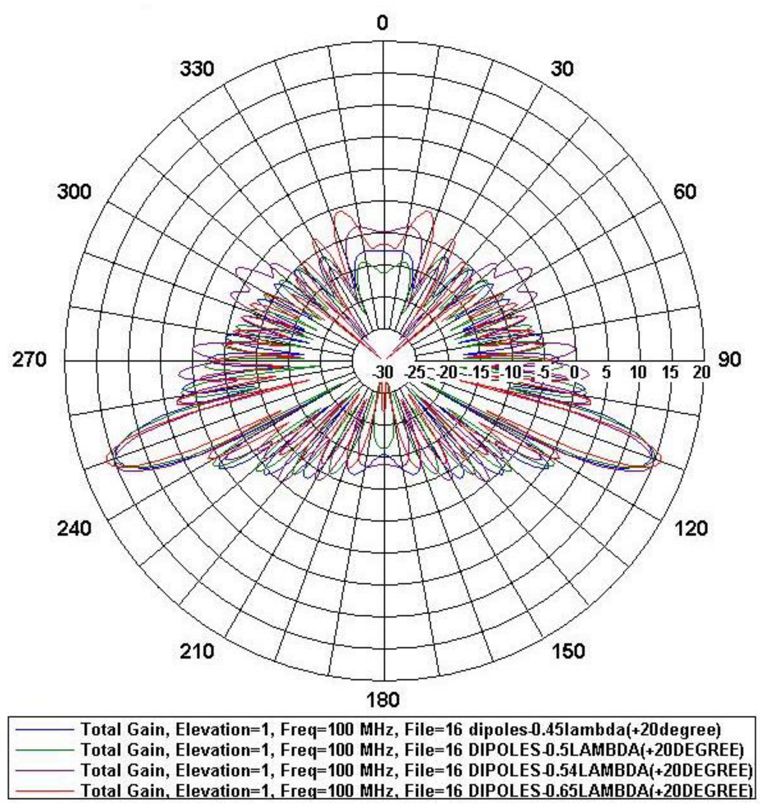

Figure 46: Azimuth Patterns of Arrays with Different Element Spacings
(20 Degrees off Boresight)

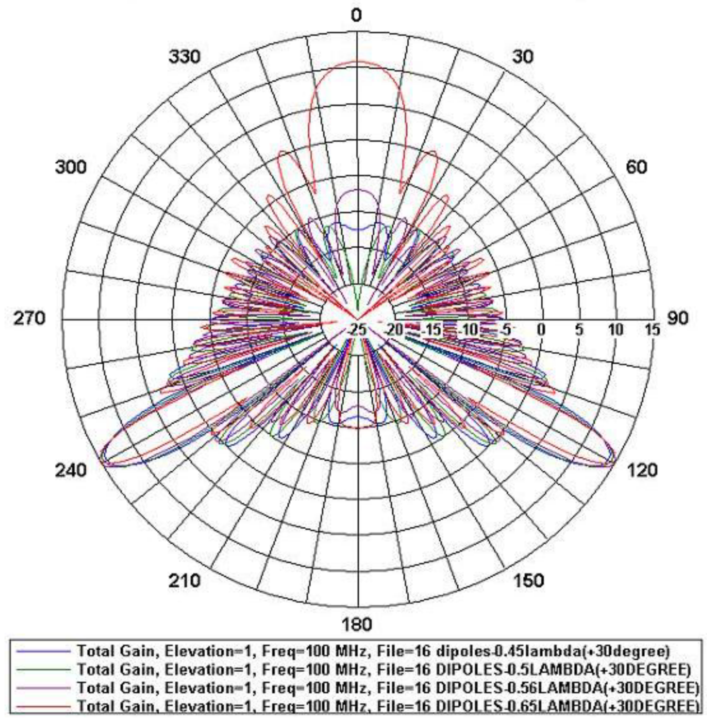

Figure 47: Azimuth Patterns of Arrays with Different Element Spacings
(30 Degrees off Boresight)

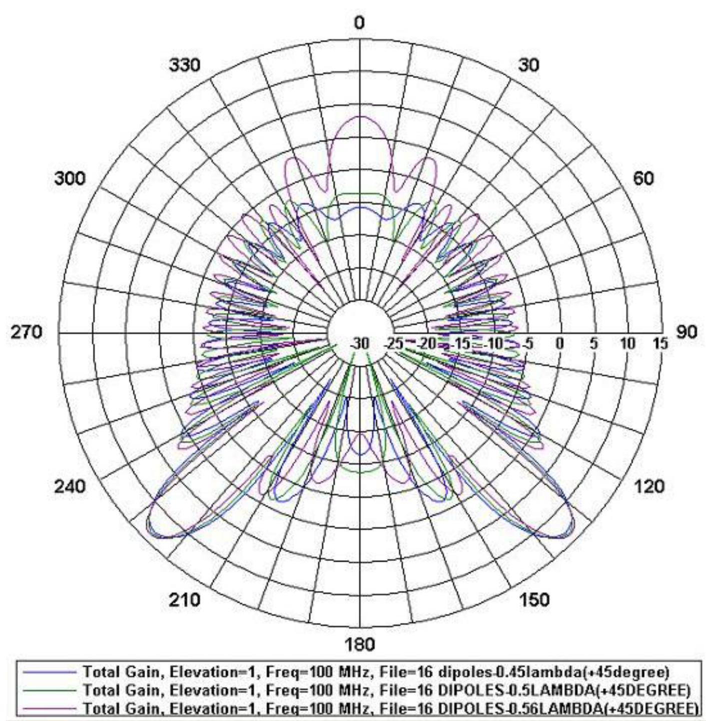

Figure 48: Azimuth Patterns of Arrays with Different Element Spacings
(45 Degrees off Boresight)

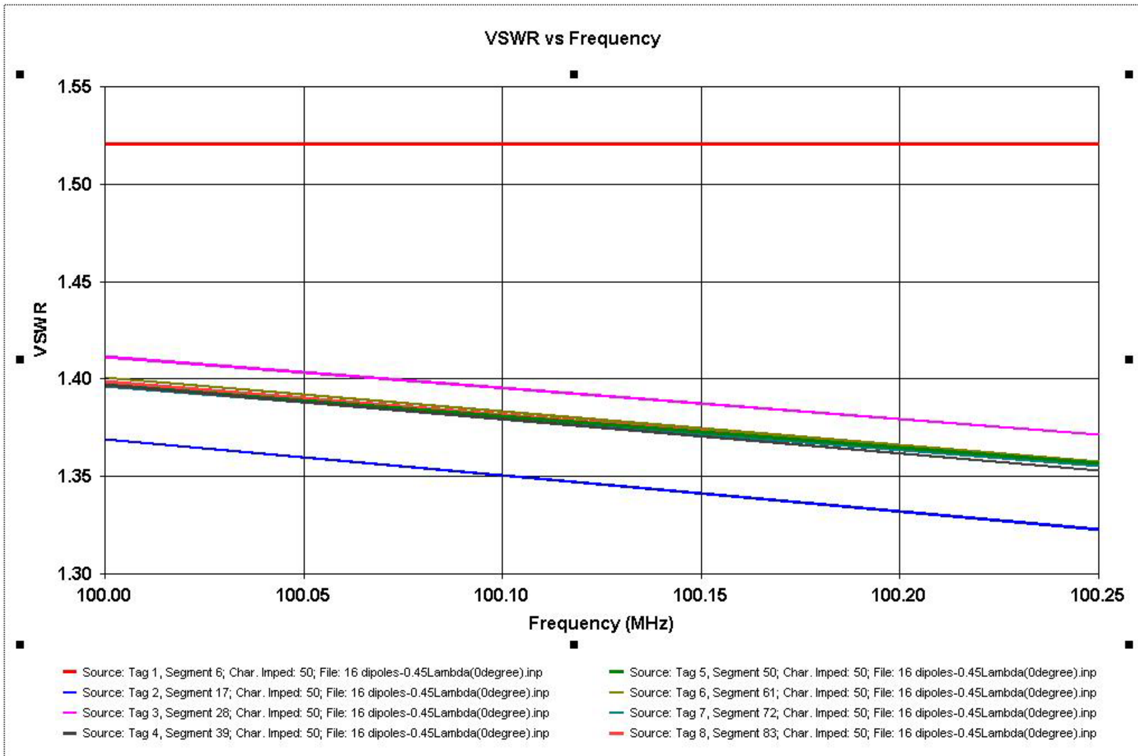

Figure 49: VSWR Values of Arrays at Boresight with Different Element Spacings (0.45λ)

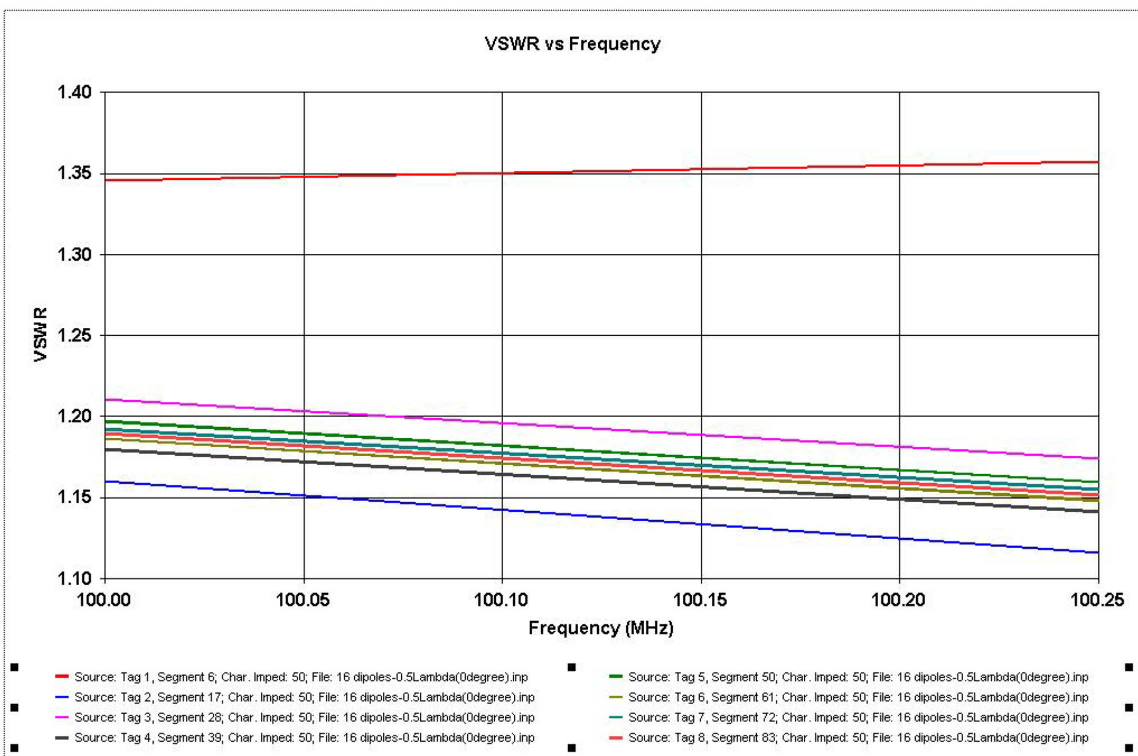

Figure 50: VSWR Values of Arrays at Boresight with Different Element Spacings (0.5λ)

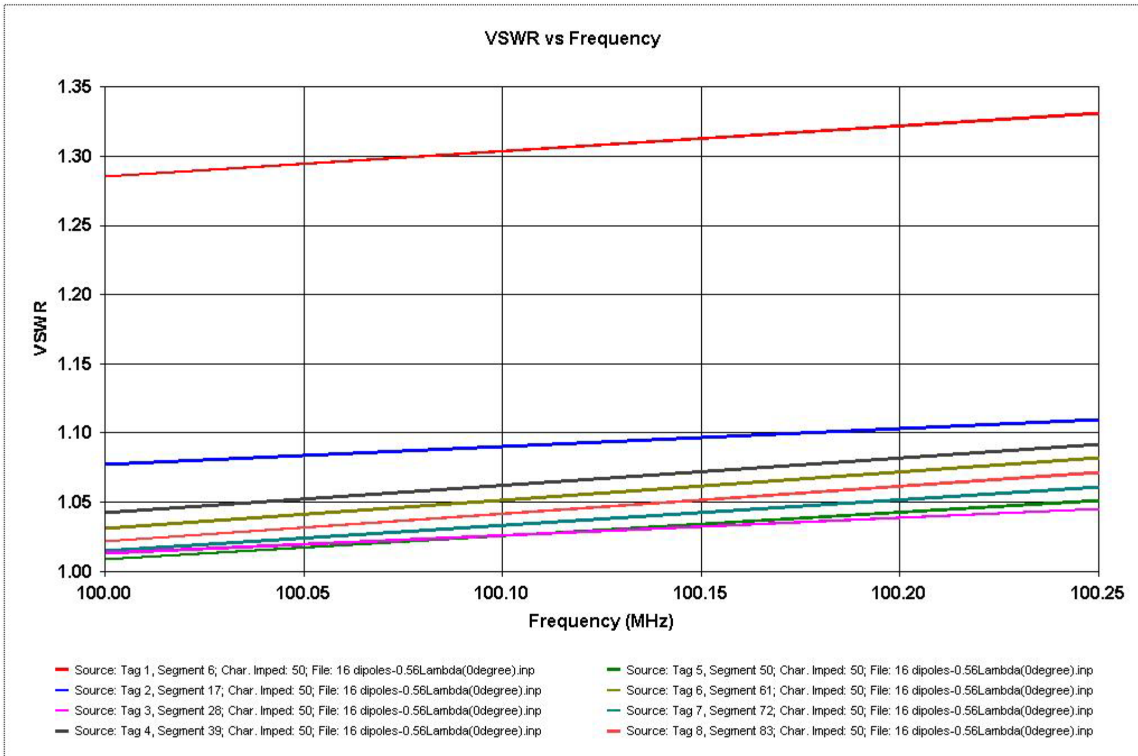

Figure 51: VSWR Values of Arrays at Boresight with Different Element Spacings (0.56λ)

<u>Observations:</u>

- Increasing the element spacing:
  - decreases the mutual coupling effect,
  - makes the main beam narrower,
  - decreases the VSWR values,
  - causes grating lobes as the angle off boresight increases.
- Grating lobe effect is one of the most important issues when designing a PCL antenna. Therefore, from Figures 45 - 48,
  - At 10 degrees off boresight, all element spacings seem reasonable.

- At 20 degrees off boresight, still they are reasonable.
- At 30 degrees off boresight, array with 0.65λ element spacing has unacceptable grating lobe.
- At 45 degrees off boresight, the array with 0.56λ element spacing has unacceptable grating lobe.

- The array with 0.45λ has the largest VSWR values.
- 0.50λ element spacing can be a satisfactory value for PCL array design considering the trade-off of the desired maximum look angle and mutual coupling effect.

4.2.4 Sub Arrays (Parasitic Elements)

Using parasitic elements (which are a bit shorter than the fed elements, and which are not driven) as directors increases the main beam gain. Figure 52 shows an azimuth pattern of a 16-element array with parasitic elements on the positive Y-axis. Figure 53 shows the new VSWR values of the array caused by the parasitic elements, respectively:

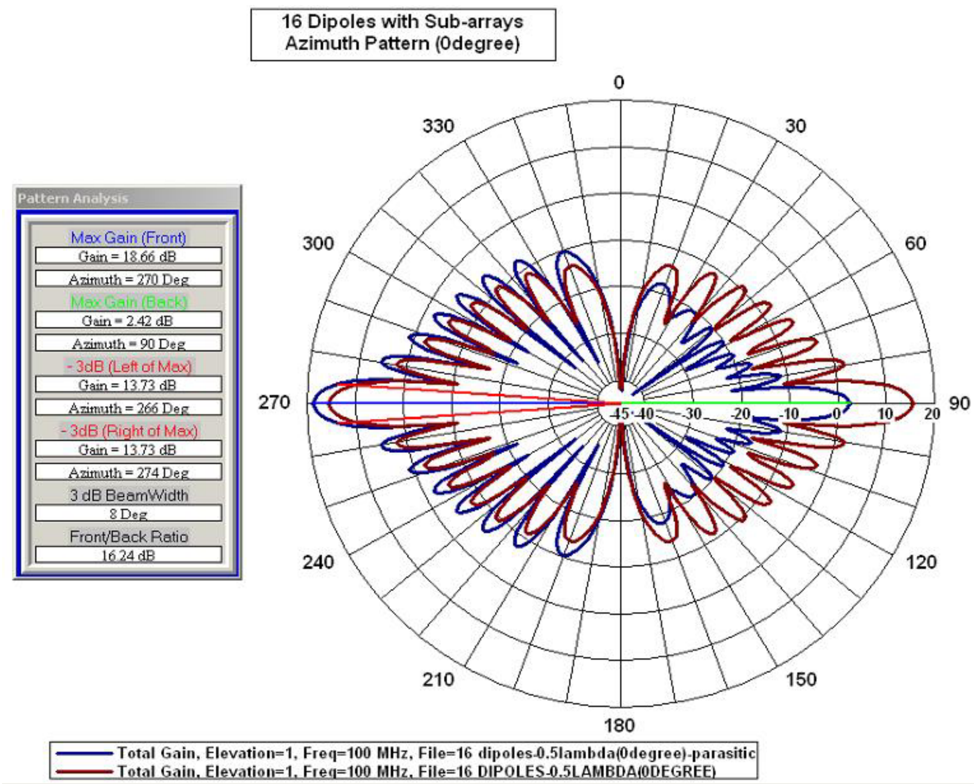

Figure 52: Effect of Using Parasitic Element on Azimuth Pattern

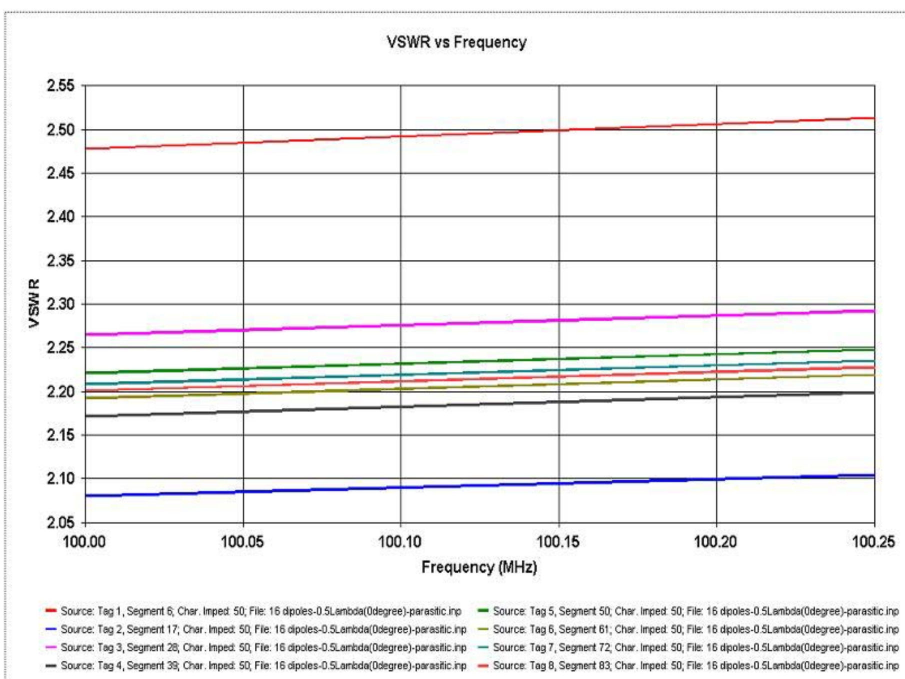

Figure 53: Effect of Using Parasitic Element on VSWR Values

Observations:

- Using parasitic elements will increase the mutual coupling effects among the elements, which will cause degrading the received signal.
- Since parasitic elements work as reflectors the main beam gain increases as well as the sidelobe gain.
- Because signal precision and minimum mutual coupling are the critical requirements for a PCL system, using parasitic elements for increasing the gain can be ignored.

4.2.5 Media

First test, which has the results of Figure 54, is placing the array antenna at different heights (5m, 10m, 15m, 20m, 30m, and 42m) above an average ground. The purpose of this test is to find the best possible height for an array antenna.

Second test, which has the results of Figure 55, is placing the array antenna at a random height (10meters) above the ground that has different qualities (very good, average, and the worst). The purpose of this test is to analyze and to compare the changes in the antenna characteristics, which are caused by the ground structure. The VSWR values of these ground types are given in Table 11, respectively.

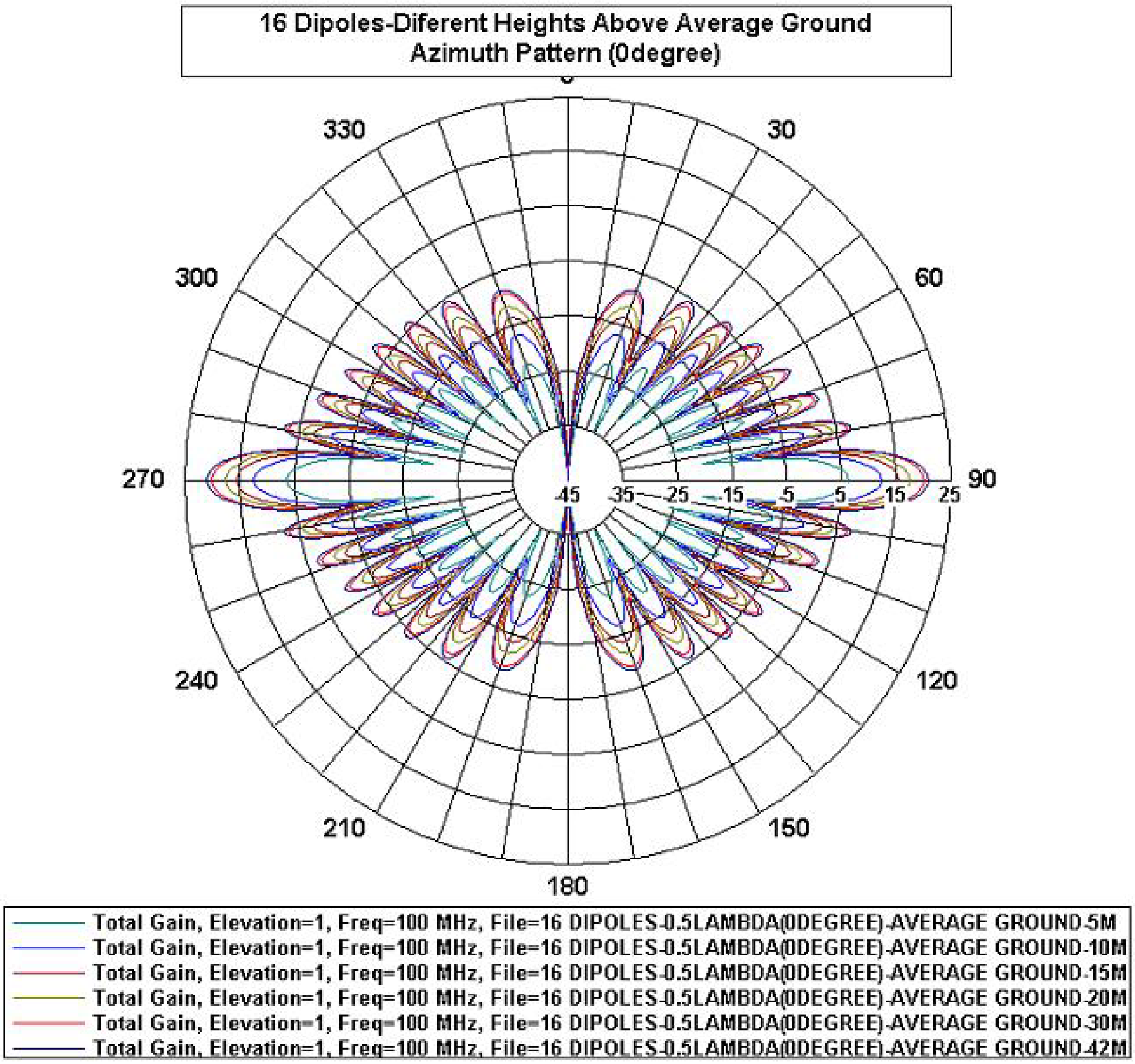

Figure 54: Azimuth Patterns at Different Heights on the Average Ground

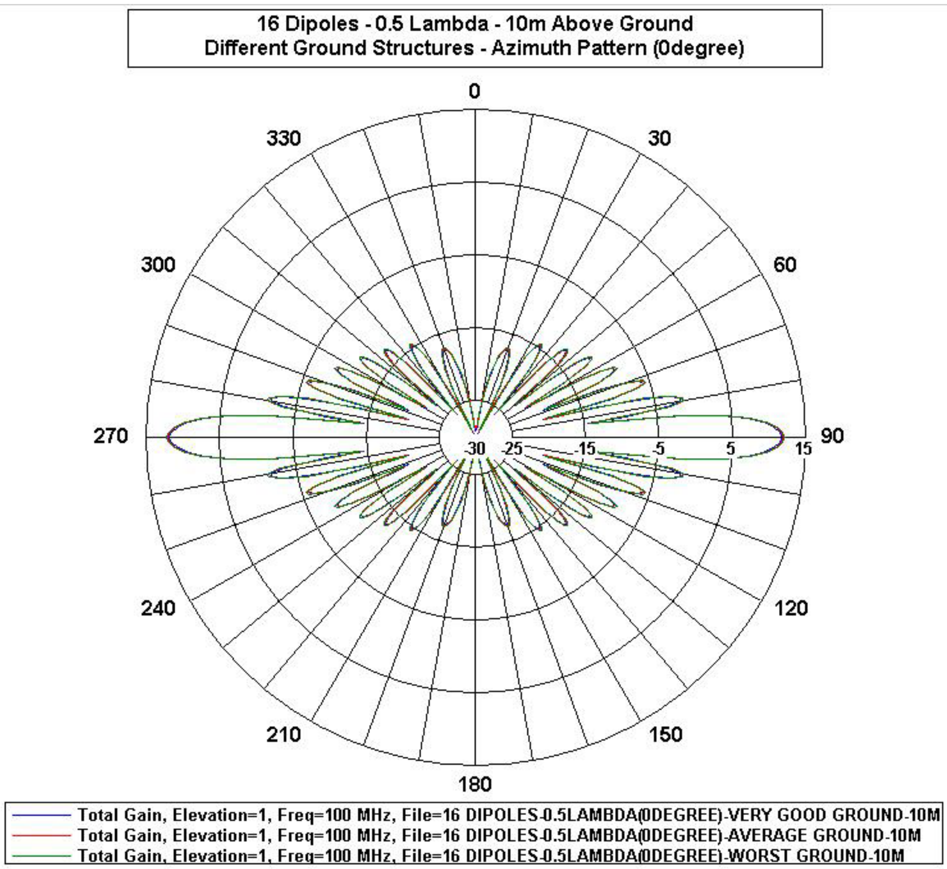

Figure 55: Azimuth Patterns for Different Ground Structures (10meters)

Table 11: VSWR Values for Different Ground Structures (10meters)

	Very Good Ground	*Average Ground*	*Worst Ground*
VSWR Range	1.1637 – 1.3451	1.1636 – 1.3451	1.1620 – 1.3453

<u>Observations:</u>

- Changing the ground structure mainly has an effect on radiation patterns.
- Better ground parameters slightly increase the main beam gain.
- Changing ground parameters slightly changes the VSWR values.

- An array antenna that is approximately 5λ (~15meters) above the average ground has almost the same azimuth pattern as in free space (for the frequency of 100MHz).

- Array antenna that is approximately 14λ (~42meters, which can be impractical) above the average ground has the maximum gain (for the frequency of 100MHz).

4.2.6 Sidelobe Level Reduction Techniques

In this test, Binomial, Chebyshev and Taylor arrays will be analyzed and compared with the uniform array designs. In Figure 56, the azimuth pattern of each array design {Binomial, Chebyshev (-26dB and –40 dB), and Taylor (-26dB and –40dB)} is shown. Also, Table 12 shows the VSWR rectangular plot of each array {Binomial, Chebyshev (-26dB and –40 dB), and Taylor (-26dB and –40dB)}, respectively.

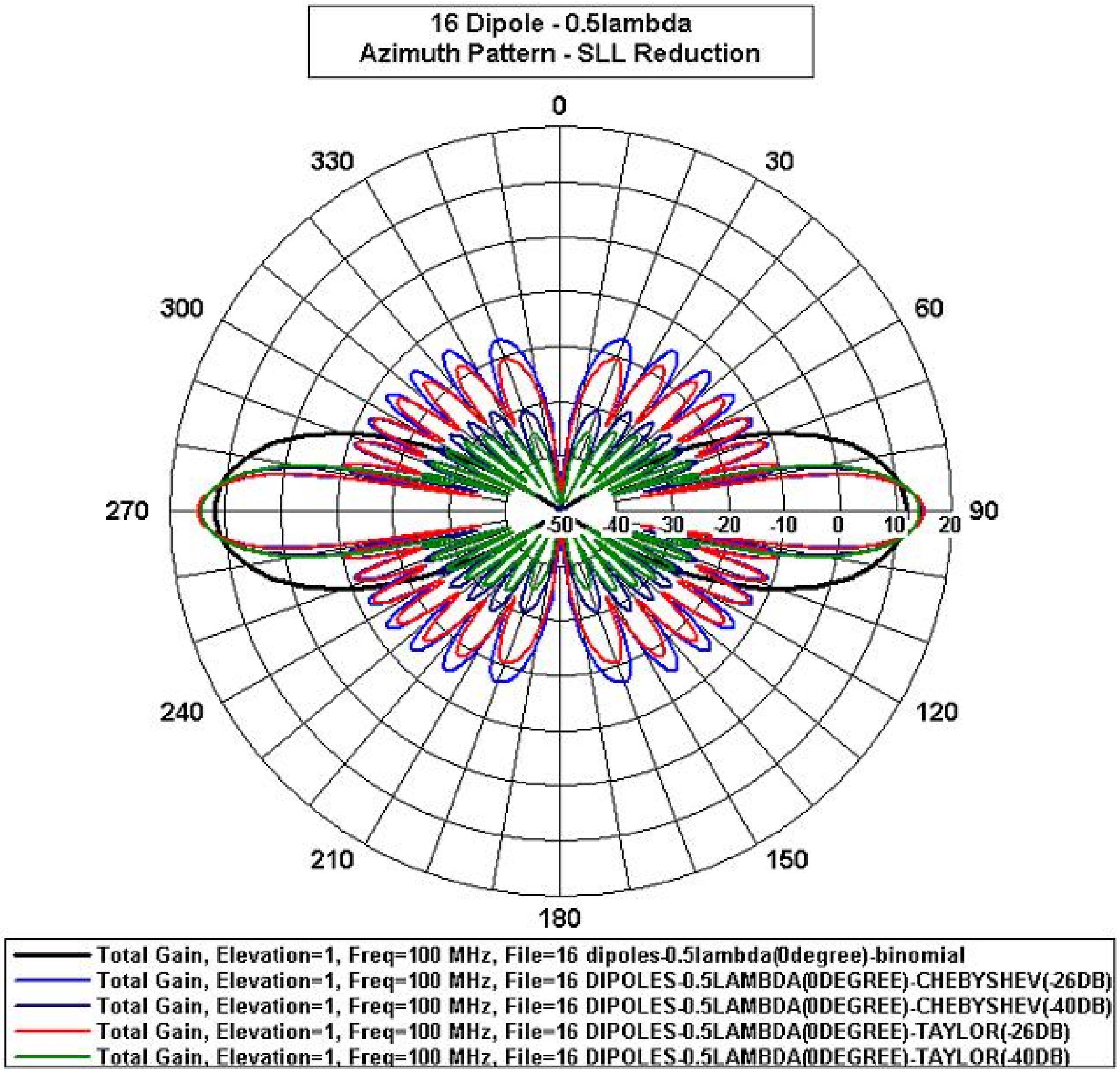

Figure 56: Azimuth Pattern of Binomial, Chebyshev and Taylor Arrays

Table 12: VSWR Ranges for the Arrays with Amplitude Tapering

	Binomial Array	*Chebyshev Array(-26dB)*	*Chebyshev Array(-40dB)*	*Taylor Array(-26dB)*	*Taylor Array(-40dB*
VSWR Range	1.19 – 2.72	1.17 – 1.40	1.19 – 1.24	1.18 – 1.25	1.19 – 1.20

Observations:

- The Binomial Array has no sidelobes, however the main beam is unacceptably wide.
- "The Chebyshev array is considered optimum in the sense that the first null beamwidth is minimum for a specified sidelobe level" [2].
- Since the Taylor Arrays are more commonly used in radar systems due to their convenience, it will be more practical and functional to use them in PCL systems.

4.3 Potential Array Antenna Designs for PCL Systems

4.3.1 Potential Array Antenna Definitions

After analyzing many array antenna models and designs, in this section there are two array designs proposed, which can be possible for PCL systems. These two antennas have the same characteristics, except for the amplitude excitation.

- Element designs will be dipoles, since they are more practical, more simple, and cheaper. Dipoles provide better covert operation, and also are as effective as the other element designs.
- Element spacing is 0.5λ since it is a compromise between maximum desired look angle and lowest VSWR values.

- Element material is pure aluminum since it is a compromise between material loss and cost.
- Media is average ground since it is more practical and more realistic, and antenna height will be approximately 20m above this ground type.
- Diameter is 5mm since it is a compromise between being solid and resulting in low VSWR values.
- There will not be any parasitic elements since they may lower the efficiency of the PCL system by increasing the mutual coupling among the elements.
- Sidelobe level reduction techniques of Chebyshev Array and Taylor Array with –26dB SLL will be applied to array antenna designs. This decision is made with respect to the Chebyshev and Taylor Arrays efficiency charts given in [23]. For a 16-element array, SLL of –26dB will make the amplitude tapering techniques to be more efficient. Besides, $\bar{n}$ =5 will be applied to Taylor Arrays due to its efficiency. The charts of Chebyshev and Taylor array efficiencies are shown in Figure 57 and Figure 58.

"Aperture efficiency is the ratio of the *effective area* of an antenna, which measures its ability to respond to radiation of a particular polarization, to its geometrical area" [4]. "*Effective Area* can be defined as the measure of an antenna system's ability to respond to radiant energy, such that the power density (per

unit area) of the radiation times the effective area of the antenna measures the power delivered by the antenna to its receptors" [23].

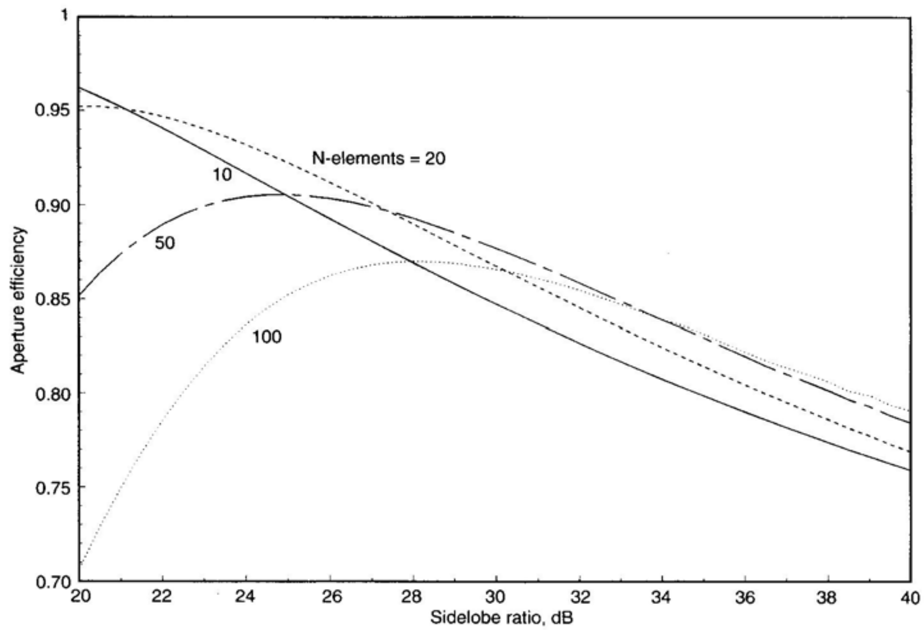

Figure 57: Chebyshev Array Efficiency for d=0.5λ

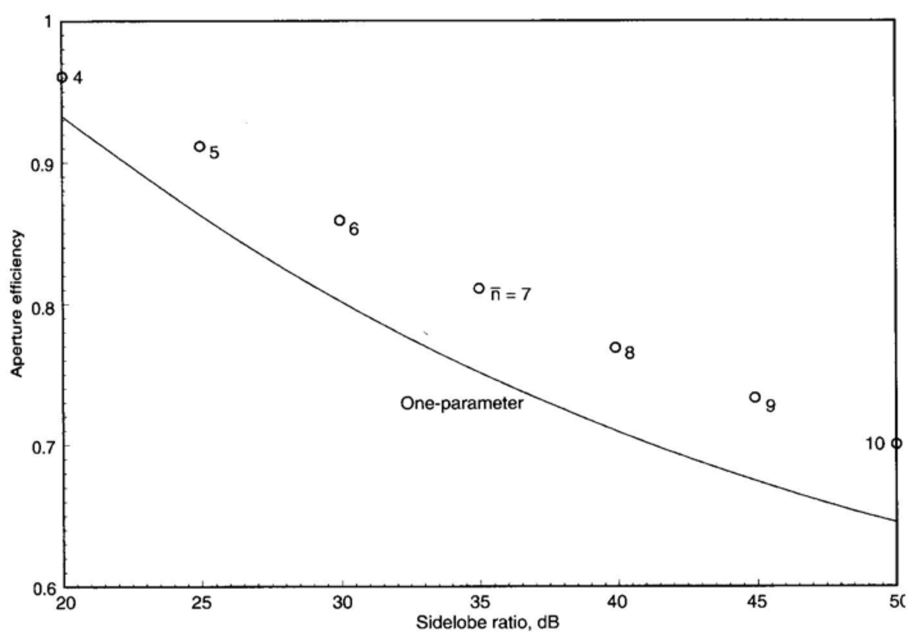

Figure 58: Taylor Array (one parameter and n-bar) Efficiency

4.3.2 Analysis and Comparison of the Characteristics of the Potential Array Antennas Simulating Actual Conditions

Having the parameters that are mentioned above, these two array antennas are simulated to study the operation characteristics. The conditions that the antennas are operating are designed considering the actual surroundings.

When designing an array antenna for a PCL system, one side of the antenna must be shielded in order to eliminate the back lobe. This process can be accomplished by locating the antenna on the wall of a building or on a surface of a van. Doing so will eliminate the back lobe and prevent ambiguity. The basic geometry of shielding (or isolation) is shown in Figure 59.

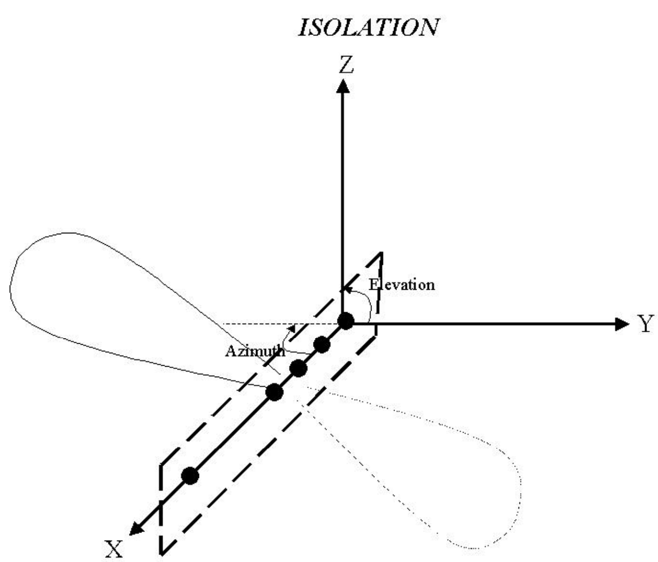

Figure 59: Basic Geometry of Isolation of an Array Antenna

Figures 60-63 and Table 13 show the results of the operational characteristics of potential antennas for different look angles.

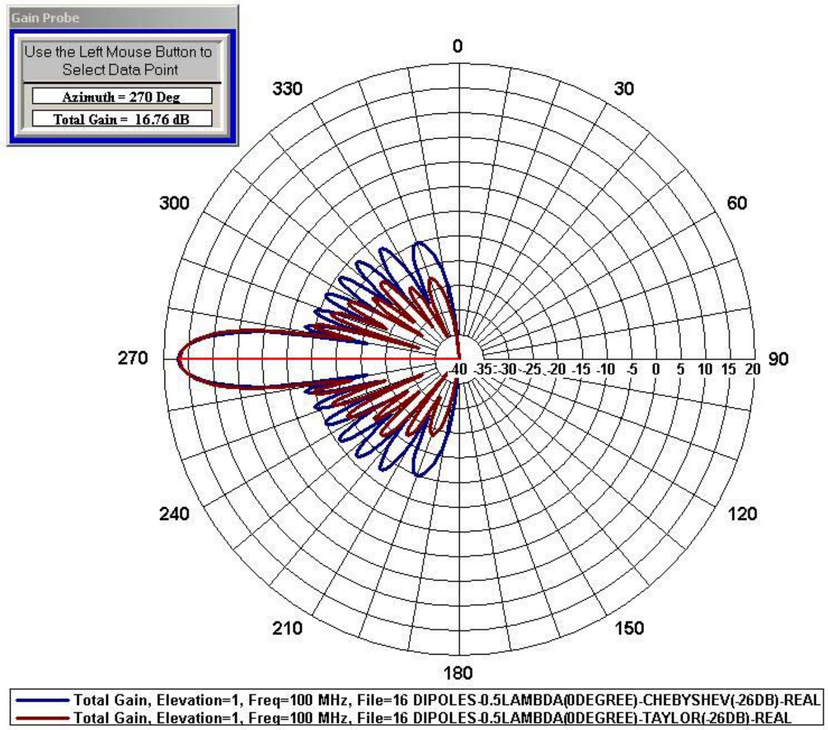

Figure 60: Azimuth Pattern of Potential Arrays at 0 Degree

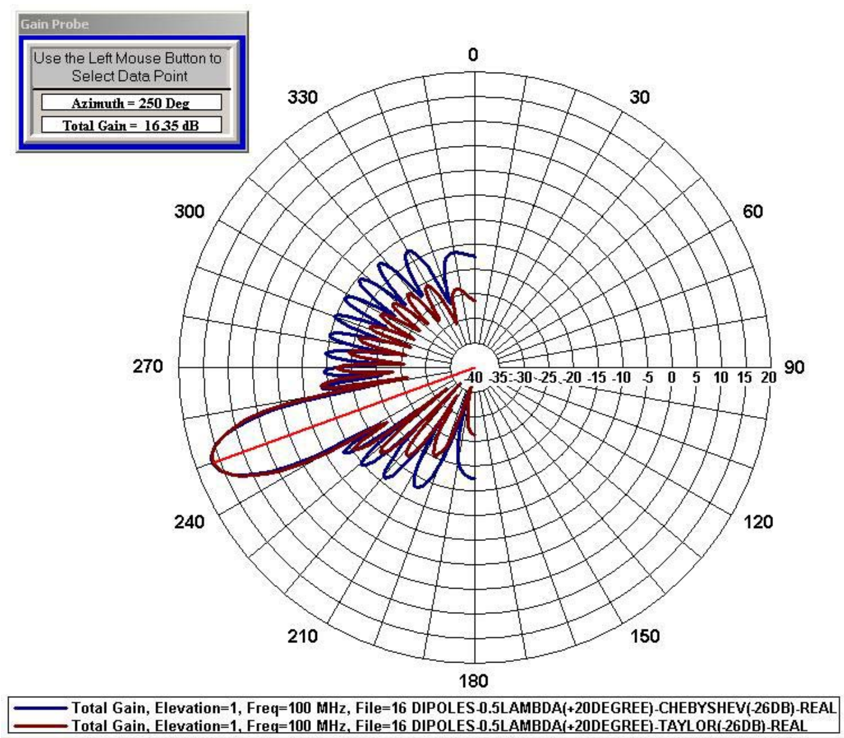

Figure 61: Azimuth Pattern of Potential Arrays at 20 Degrees

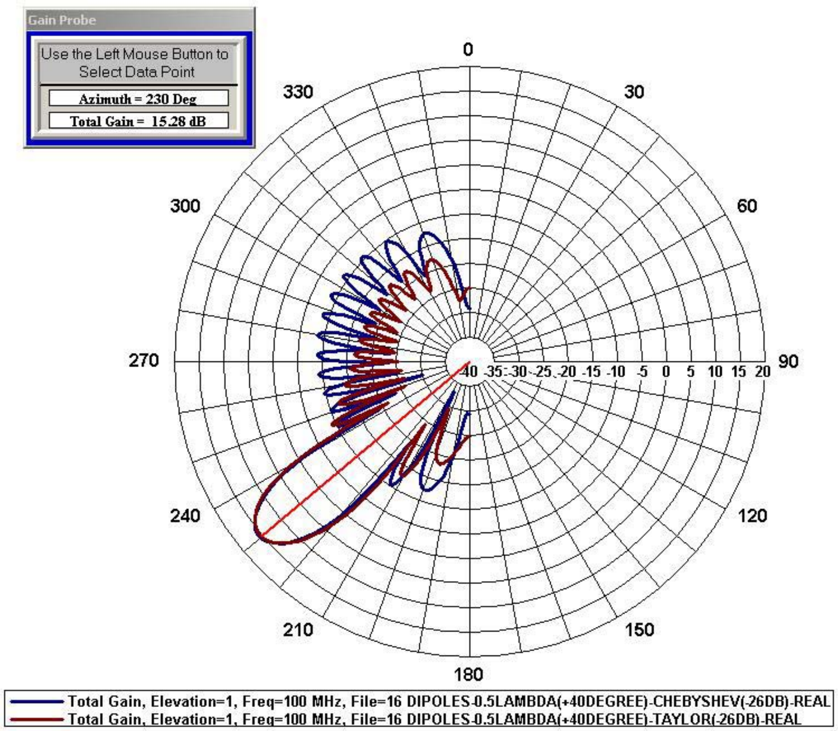

Figure 62: Azimuth Pattern of Potential Arrays at 40 Degrees

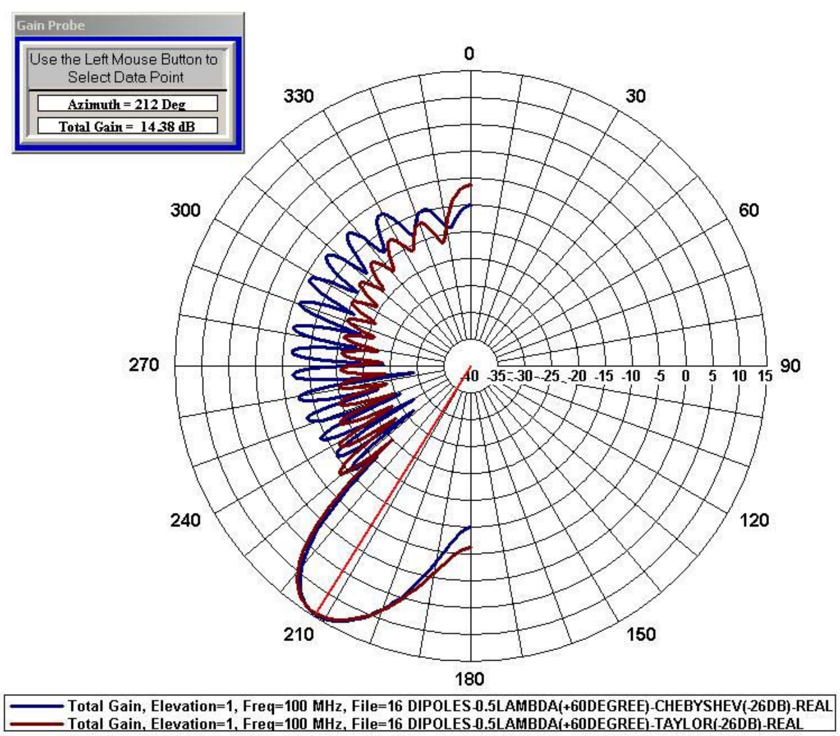

Figure 63: Azimuth Pattern of Potential Arrays at 60 Degrees

Table 13: VSWR Values of Arrays at Different Look Angles

	0 Degree	*20 Degree*	*40 Degree*	*60 Degree*
Chebyshev Array (-26dB)	1.18-1.40	1.22-1.63	1.69-2.03	2.26-4.51
Taylor Array (-26dB)	1.17-1.25	1.15-1.63	1.73-2.15	2.93-4.40

Observations:

- These two array designs have slight differences in their operation characteristics, yet both of them have reasonable results. Both arrays passed the *Average Gain Test* in NECWin Plus, which performs many checks to alert if there are potential problems with the design.

- Both arrays operate reasonably up to the look angle exceeds 50 degrees. Between 50 and 70 degrees of look angle, they need calibration in order to get accurate measurements. Beyond 70 degrees they are not dependable for DOA estimation.

- VSWR values and element input impedances are moderately acceptable in order to have efficient receiving.

- All in all, these arrays can be used for PCL systems, which will facilitate better measurements.

- Power efficiency of the antennas is above 99% since aluminum is the material for the elements.

4.3.3 Analysis and Comparison of DOA Estimation Techniques of Potential Array Antennas for PCL Systems

The arrays that were mentioned previously (Chebyshev Array with –26dB SLL and Taylor Array with –26dB SLL) will be applied to MATLAB codes generated and modified by Ozcetin [13]. This will show the efficiency of the array antennas in DOA estimations for different DOA techniques. The test criteria that were mentioned in *Section 3.5.2.2* will be utilized for the objects with different SNR values. Doing so will test the array antenna characteristics for different signal strengths.

4.3.3.1 High SNR Scenario {SNR_1=+10dB, SNR_2=+10dB}

Both returned signals from the objects have the SNR value of +10dB. These values of the returned signals will evaluate the array antennas for strong signals. This can be interpreted as a situation where the objects are close in range to the receiver. Results are shown in Figure 64 and Figure 65.

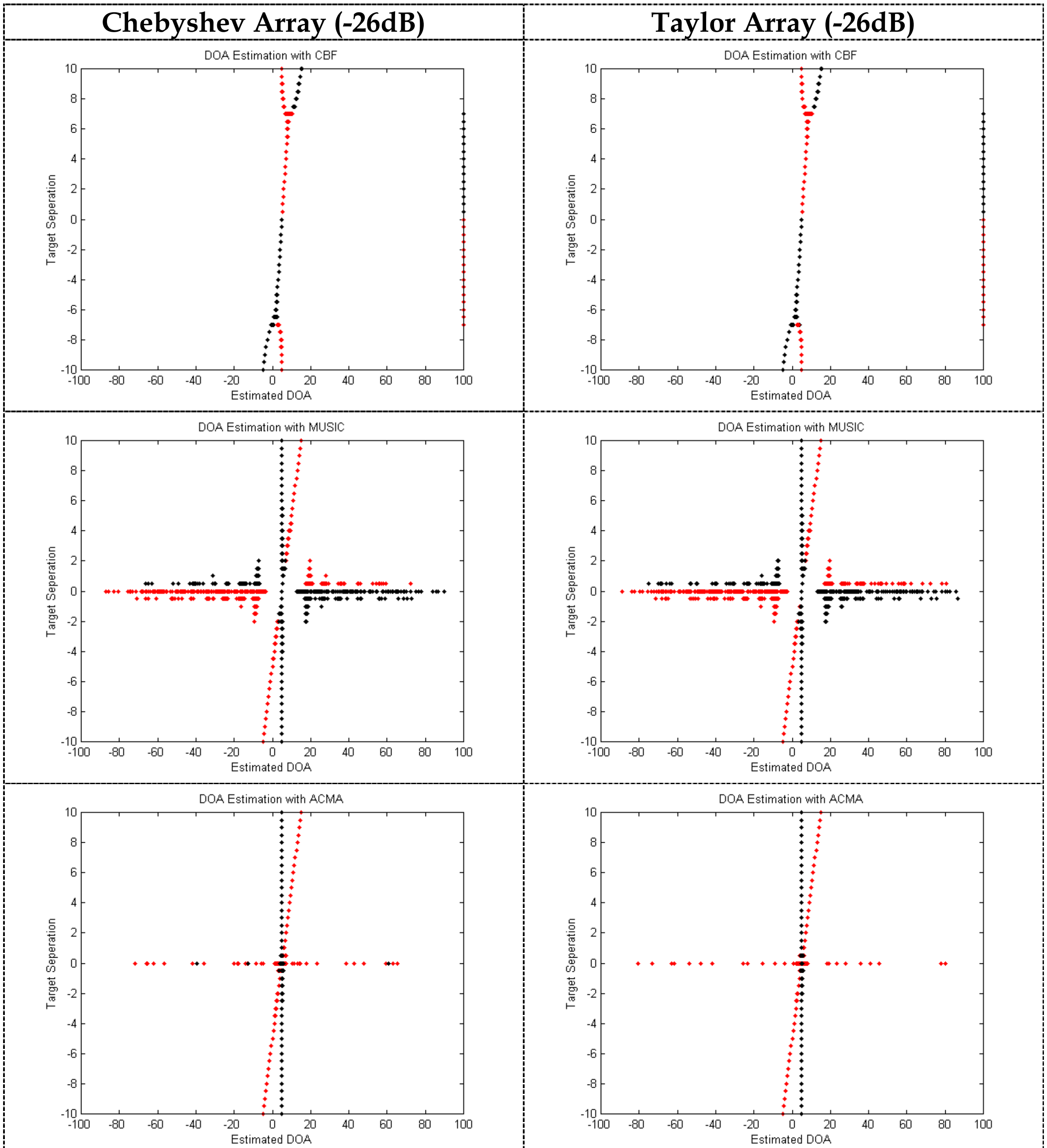

Figure 64: DOA Estimation Comparison of the Arrays {SNR=+10, +10}

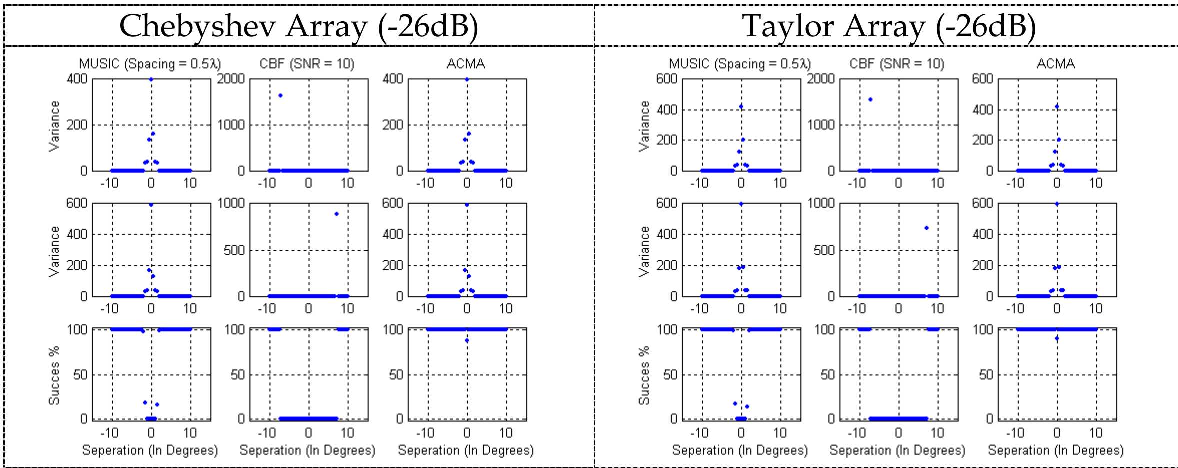

Figure 65: Variance and Success Rates of the Arrays {SNR= +10, +10}

4.3.3.2 High/Low SNR Scenario {SNR_1=-10dB, SNR_2=+10dB}

One of the returned signals from one object has the SNR value of -10dB and the other one has the SNR value of +10dB. These values of the returned signals will evaluate the array antennas for incoming weak and strong signals. This can be interpreted as a situation where the objects are close in range to the receiver. Results are shown in Figure 66 and Figure 67.

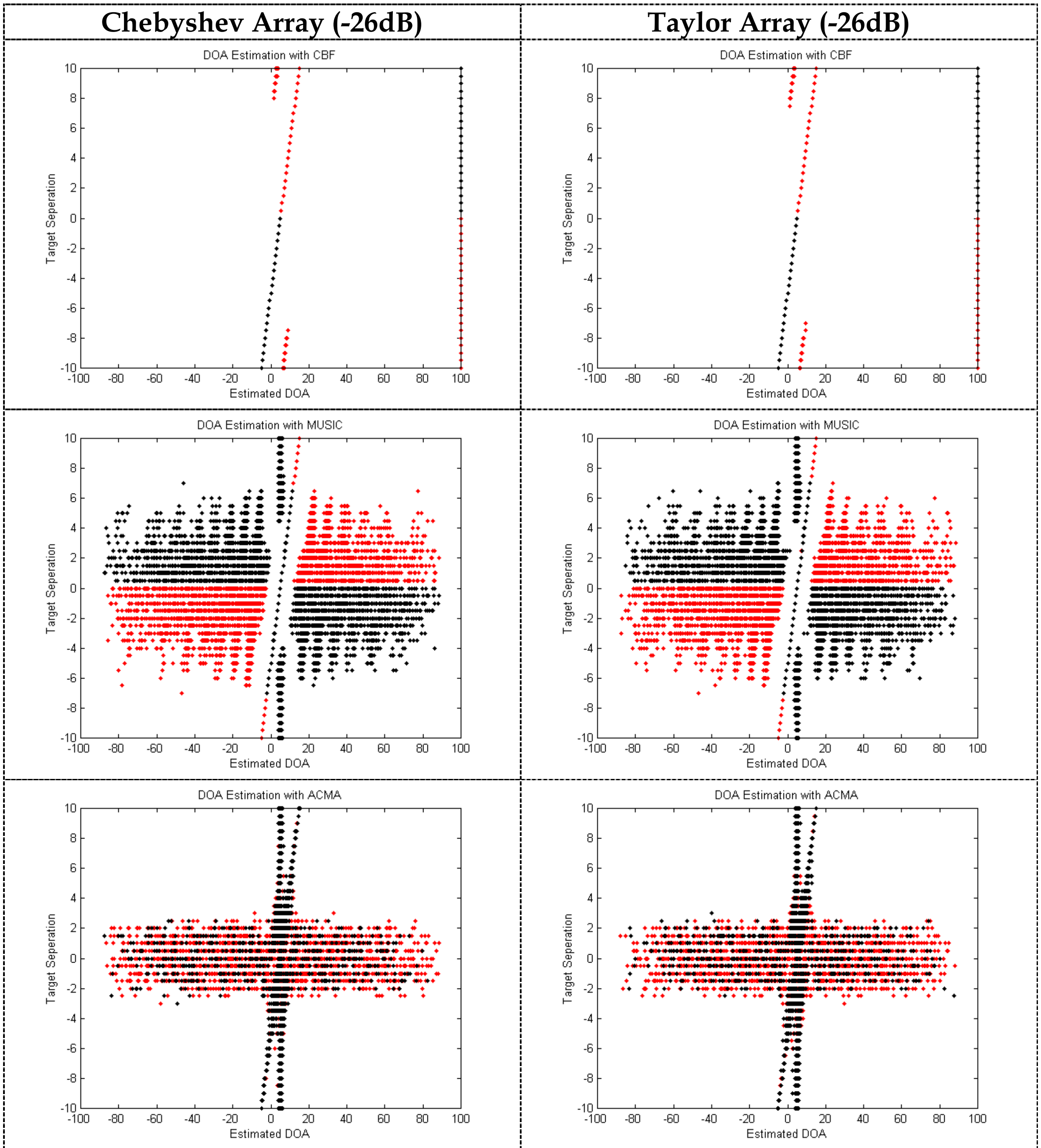

Figure 66: DOA Estimation Comparison of the Arrays {SNR=-10, +10}

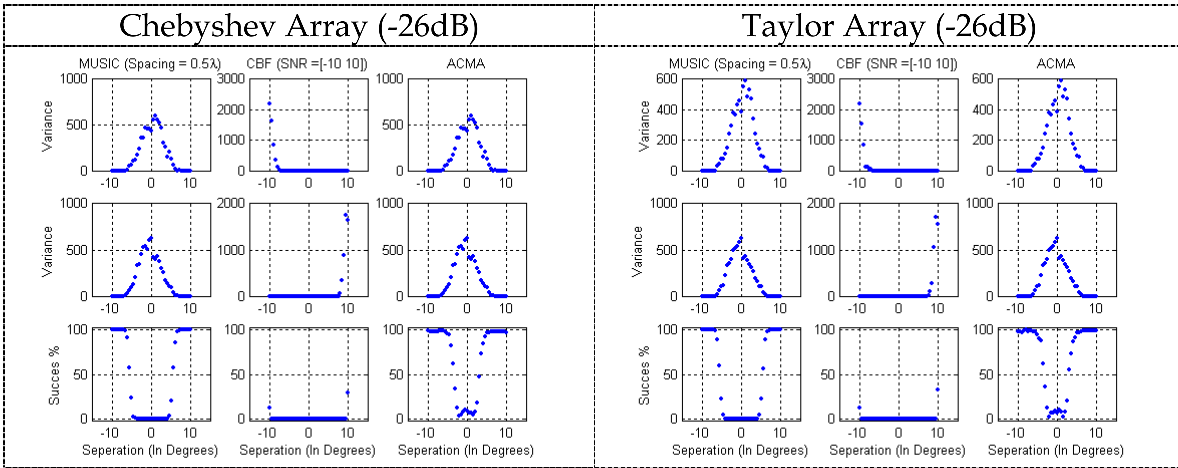

Figure 67: Variance and Success Rates of the Arrays {SNR=-10, +10}

4.3.3.3Low SNR Scenario {SNR_1=-10dB, SNR_2=-10dB}}

Both returned signals from the objects have the SNR value of -10dB. These values of the returned signals will evaluate the array antennas for weak signals. This can be interpreted as a situation where the objects are close in range to the receiver. Results are shown in Figure 68 and Figure 69.

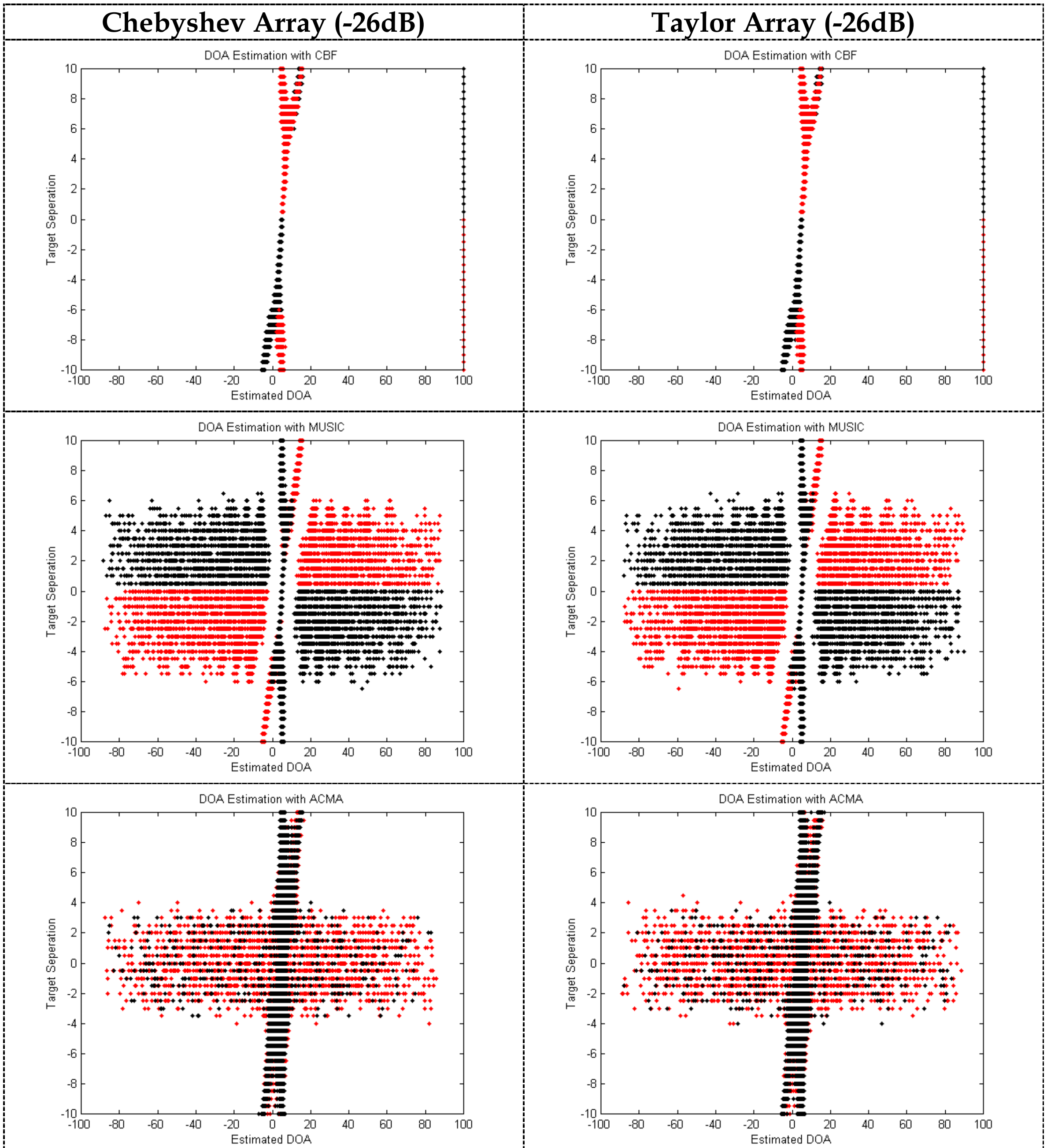

Figure 68: DOA Estimation Comparison of the Arrays {SNR=-10, -10}

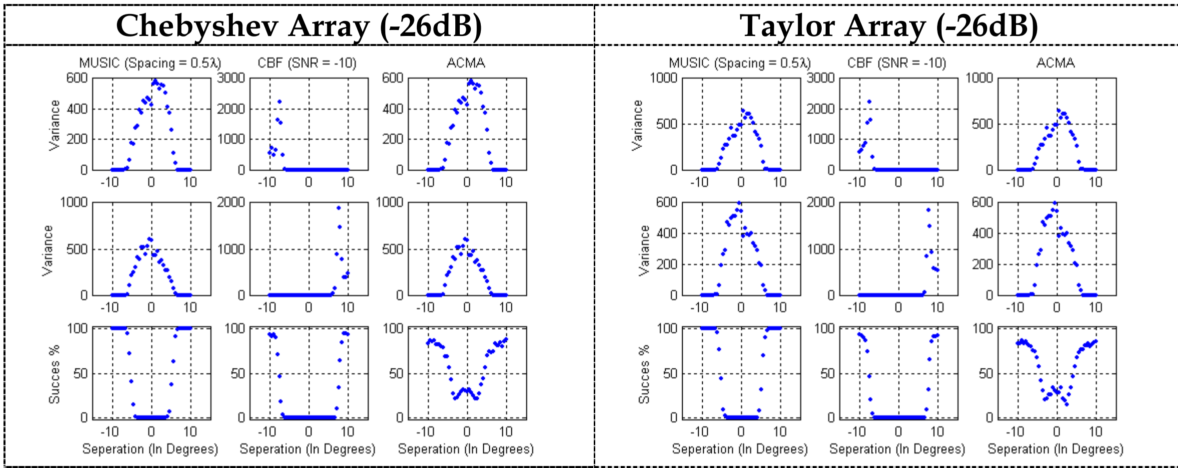

Figure 69: Variance and Success Rates {SNR=-10, -10}

Observations:

- These two array antennas with different amplitude tapering techniques have almost the same characteristics when applied in DOA estimators.
- For high SNR values, resolution is fairly good, separation is achieved almost 100 percent, and variances are reasonable for each object.
- When SNR values are low, DOA estimation degrades as the resolution becomes worse, the separation success decreases, and the variance of each object increases.
- Considering the results shown above, ACMA, which has not been previously applied to PCL systems, is the most advantageous DOA estimator. This DOA estimation can be a turning point for PCL systems.

Chapter 5 - DISCUSSION

5.1 Importance of the Array Antennas for PCL Systems

There are many advantages of using an array antenna for a PCL system. However, because the array antenna for a PCL system functions theoretically as *a receiver only phased array antenna*, there are some slight differences. The advantages of using an array antenna for a PCL system are as follows:

- Using more channels will narrow the beam which will result in better resolution,
- Array elements that are functioning together will increase the gain,
- New DOA estimation techniques will be convenient and applicable for PCL designs,
- Increased number of elements will yield have more information and aspect about the incident wave,
- It will enable the exploitation of the features of the incoming signal,
- Using array antennas will allow taking advantage of array features, such as sidelobe reduction techniques.

Considering these important and useful advantages, using array antennas for PCL systems instead of traditional Yagi Uda antennas is an obvious engineering decision.

5.2 Future Work

This work is done only for 100MHz since the FM radio stations are the transmitters of opportunity and since this frequency is ideal as the middle frequency for FM bandwidth. However, dipoles are not broadband elements, and therefore the antenna that is designed for 100MHz will not be as efficient as for other frequencies.

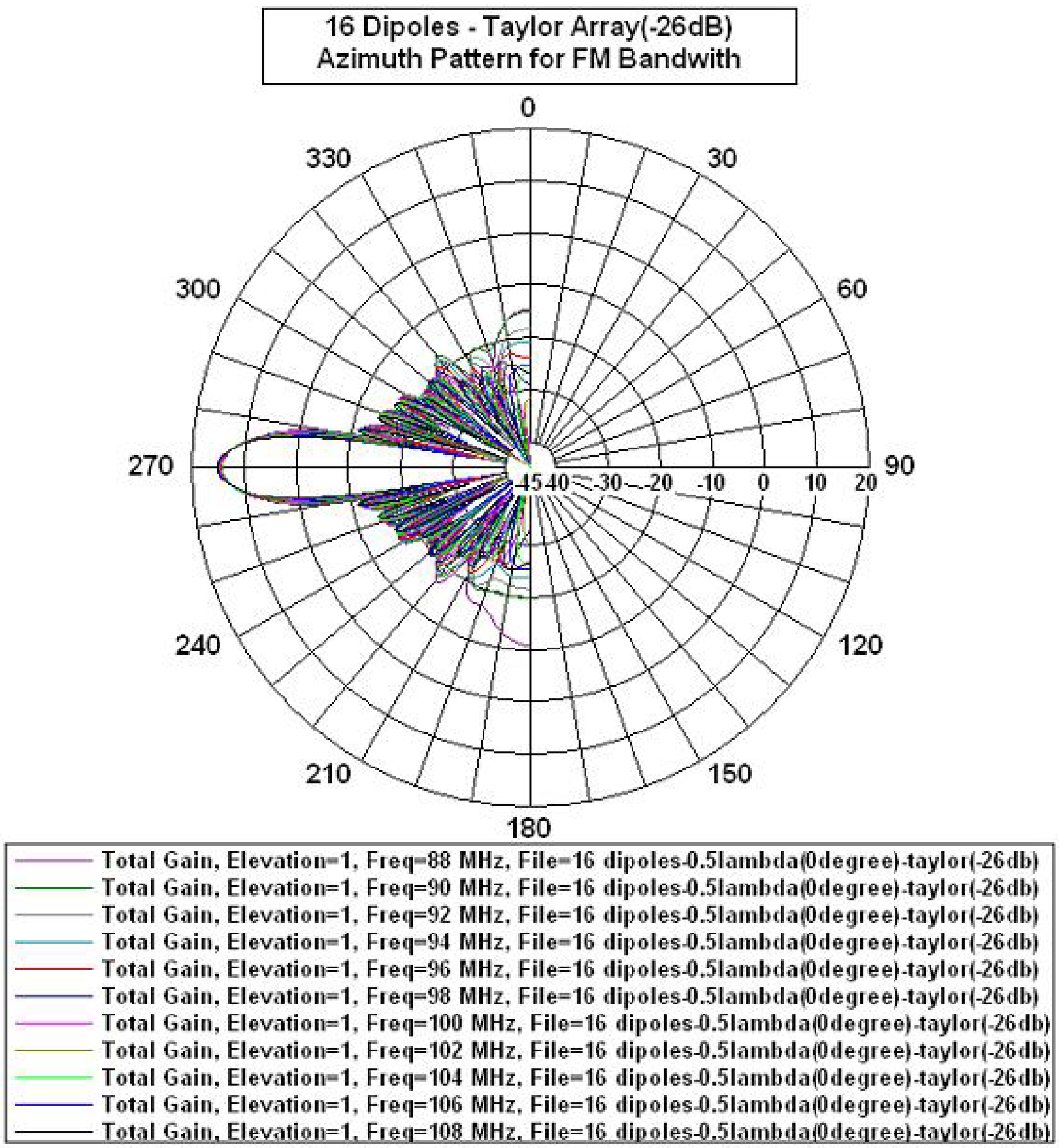

Figure 70: Azimuth Pattern of Taylor Array (-26dB) Operating at 88-108MhHz

Figure 70 shows the azimuth pattern of one of the potential array antennas for PCL systems, operating at FM Bandwidth. Azimuth patterns are computed for every 2 MHz starting from 88MHZ and ending at 108MHz. All of the conditions are a stated previously. As seen in the figure, radiation pattern have almost the same main beam characteristics with a little difference sidelobe characteristics. However, VSWR values change drastically especially at the edge frequencies as seen in Figure 71. This will decrease the power efficiency of the array antenna for other frequencies.

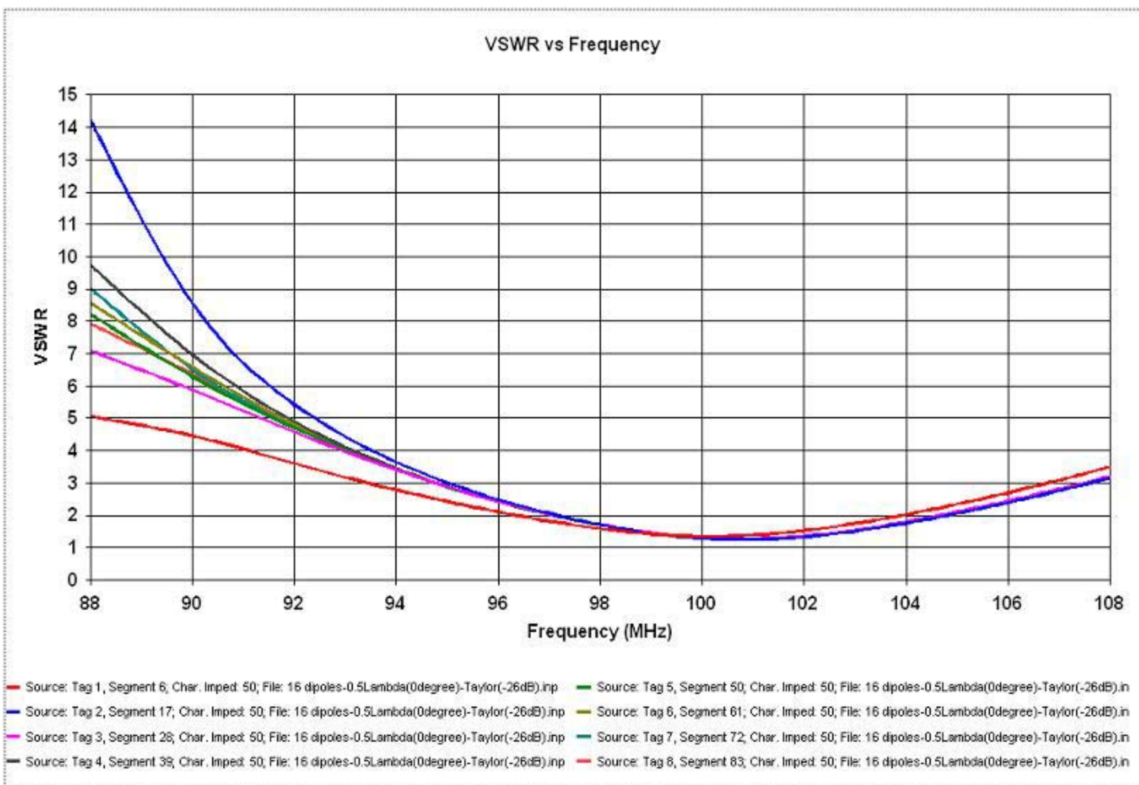

Figure 71: VSWR Values of Taylor Array (-26dB) Operating at 88-108MhHz

In order to get the same efficiency, the element spacings and the element lengths should be modified for that frequency. There are several ways to solve this problem:

- Using broadband elements such as sleeve dipoles,
- Designing many antennas for every frequency that will be exploited,
- Making an array design that is flexible to change the element lengths and element spacings.

Since the DOA estimation in azimuth had been the focus of this research for PCL systems, only linear array antennas have been analyzed. However, planar array antennas, or even better conformal array antennas are possible applications to a PCL system. Using either planar or conformal arrays will provide the DOA estimation not only in the azimuth, but also in the elevation. Moreover, using either planar or conformal arrays is more convenient for object tracking and identification, as well as for object detection. Using these kinds of antennas will burden the signal processing, which is already too complicated due to PCL geometry.

Optimizing the array antennas for a PCL configuration is another issue. Array antenna optimization for PCL systems can be achieved by using *Evolutionary* or *Genetic Algorithms*. This will find the best solution for optimal array designs for given parameters. Since PCL systems demand a multiobjective optimization technique, genetic algorithms can be useful to achieve the best array

designs. Using genetic algorithms requires a solid background in engineering electromagnetics, antenna and array antenna theory, and specific knowledge in the theory of evolutionary algorithms and high performance computing.

APPENDIX

Linear Array Theory

There are many types of antennas each of which have rather unique features such as impedance, beam width, bandwidth, polarization, sidelobe level, and pattern shape. The physical features of an antenna, such as size and shape, are also important. Many times one would like to vary these properties without building another antenna. Sometimes it is difficult to achieve the electrical properties one desires with any one antenna in a given physical environment. As known, an antenna is a structure carrying an electrical current and the electrical properties of the antenna depends upon the distribution of that current in magnitude and phase. If one can change the current distribution of the antenna, they can change its characteristics. Given this, it is possible to build an antenna in some physically required constraint and make it look like an antenna of a different shape. Usually it is difficult to change the current distribution on an antenna that has just one feed point. If a single antenna is built with multiple feed points, it is difficult to adjust their feeds independently in order to change the current distribution. This is because a change in excitation of one feed point will, most likely, affect the impedance seen at the other feed points. If we use an array of similar antennas with a low gain, it is possible to obtain an antenna that has a higher gain and a radiation pattern that can be electronically steered.

Antennas can also be arrayed to obtain a wide bandwidth and low sidelobes if one is willing to trade off gain.

The most straightforward array is a uniformly excited linear array, made up by a straight row of elements having the same amplitude excitations. A simple linear array, with element spacing *d,* is shown in Figure A-1.

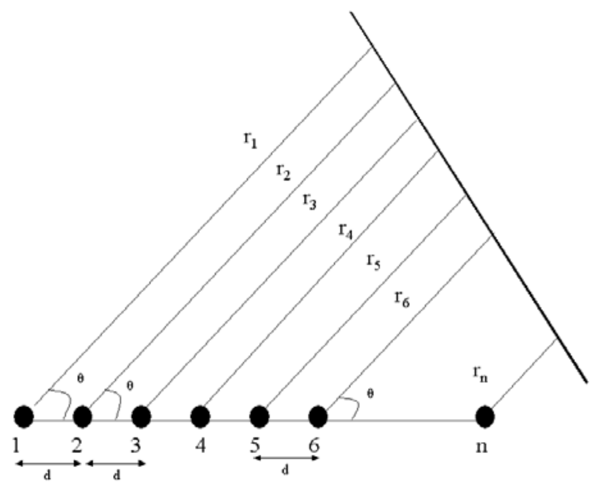

Figure A-1: Linear Array Configuration

Pattern

Each element of the array acts as a source with its own diffraction pattern $E_1(\theta)$, and the radiation from the sources interacts to form an interference pattern, which is usually called the *Array Factor (AF).* This Array Factor can be obtained by assuming N element array, with the element excitations of $I_1, I_2, I_3, \ldots, I_N$. "$I_n$ is the complex amplitude excitation, which most of the time is assumed constant for convenience" [23]. If the locations of the elements are $z_1, z_2, z_3, \ldots, z_N$, then nth element contribution to AF is given by $I_n e^{j\beta z_n \cos\theta}$, and the AF is the summation of these terms:

$$AF = I_1 e^{j\beta z_1 \cos\theta} + I_2 e^{j\beta z_2 \cos\theta} + I_3 e^{j\beta z_3 \cos\theta} + \ldots + I_N e^{j\beta z_N \cos\theta} \qquad \text{(a-1)}$$

If the element spacings are equal, which is d, this equation yields to:

$$AF = \sum_{n=1}^{N} I_n e^{j\beta n d \cos\theta} = \sum_{n=1}^{N} |I_n| e^{j(\beta n d \cos\theta + \alpha_n)} \qquad \text{(a-2)}$$

{For the equal space case: $z_1=d$, $z_2=2d$, …, $z_N=Nd$}

where, α = phase progression parameter.

Considering uniformly excited, equally spaced, linear array antenna with linear phase progression, that is:

$$I_1=1,\ I_2=e^{j\alpha},\ I_3=e^{j2\alpha},\ \ldots I_n=e^{jn\alpha},\ldots \qquad \text{(a-3)}$$

The Array Factor in this case has a closed form as:

$$AF = \sum_{n=1}^{N} e^{jn(\beta d \cos\theta + \alpha)} = \sum_{n=1}^{N} e^{jn\psi} = \frac{1 - e^{jN\psi}}{1 - e^{j\psi}} \qquad \text{(a-4)}$$

where, $\psi = \beta d \cos(\theta) + \alpha$ {ψ = phase shift}.

Ignoring the phase, the Uniformly Excited (UE), Equally Spaced Linear Array (ESLA) has the Array Factor, given by:

$$AF = \frac{\sin(N\psi/2)}{N\sin(\psi/2)} \qquad \text{(a-5)}$$

The radiating elements are usually simple devices such as dipoles, slots, patches or some times small horns. All these elements have fairly wide diffraction patterns and the antenna pattern is determined by the much narrower array factor. The Array Pattern is the product of the isolated element pattern and the isotropic Array Factor, that is:

Array Pattern = (Array Factor) x (Element Pattern)

The far-field radiation pattern is just the discreet Fourier Transform (FT) of the array excitation. The maximum radiation direction for UE-ESLA is in the direction of θ_0 such that $\beta d\cos(\theta_0)+\alpha=0$. For fixed spacing ($d$), the main beam direction is controlled by the phase progression parameter α. In other words, beam scanning is achieved by varying α.

Beamwidth

According to [23], for a beam scanned angle θ_0, *3-dB beamwidth* (θ_{3dB}) can be computed as":

$$\theta_{3dB} = \arcsin\left(\sin\theta_0 + 0.4429\frac{\lambda}{Nd}\right) - \arcsin\left(\sin\theta_0 - 0.4429\frac{\lambda}{Nd}\right) \qquad \text{(a-6)}$$

For large N ($Nd \gg \lambda$), this reduces to:

$$\theta_{3dB} \cong \begin{Bmatrix} \dfrac{0.8858\lambda}{Nd\cos\theta_0} \text{..............} \mathit{NearBroadside} \\ 2\sqrt{\dfrac{0.8858\lambda}{Nd}} \text{............} \mathit{Endfire} \end{Bmatrix} \qquad \text{(a-7)}$$

Beam collapsing near Endfire Array causes the difference between Broadside and Endfire Arrays 3-dB beamwidth.

"Figure A-2 shows the normalized beamwidth ($N_{\theta 3dB}$ or N_{u3}) as a function of the number of the elements. For $N \geq 7$, the variation in normalized beamwidth is less than 1% and the error is only 5% for N=3" [23].

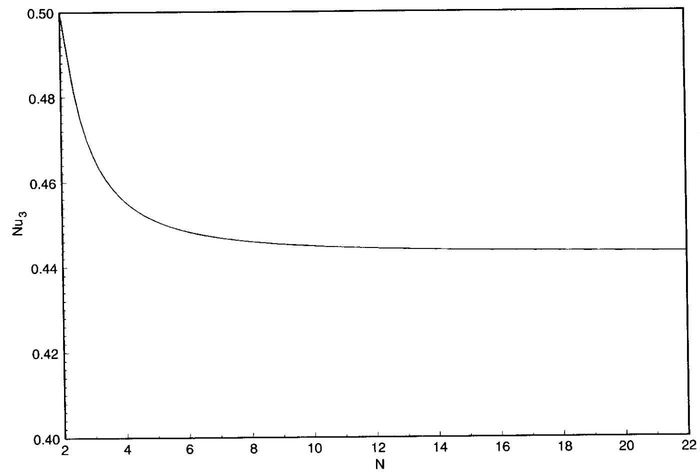

Figure A-2: Normalized Beamwidth vs. Number of Elements

Sidelobes

According to [23], Uniform Array nulls and sidelobes are well behaved and equally spaced. The nulls occur at $u=n/N$, with n=1 to N-1. Sidelobe ratio (SLR), which is the ratio of the main beam amplitude to that of the first sidelobe, is independent of the main beam angle and is the same as that for uniform line sources for large N.

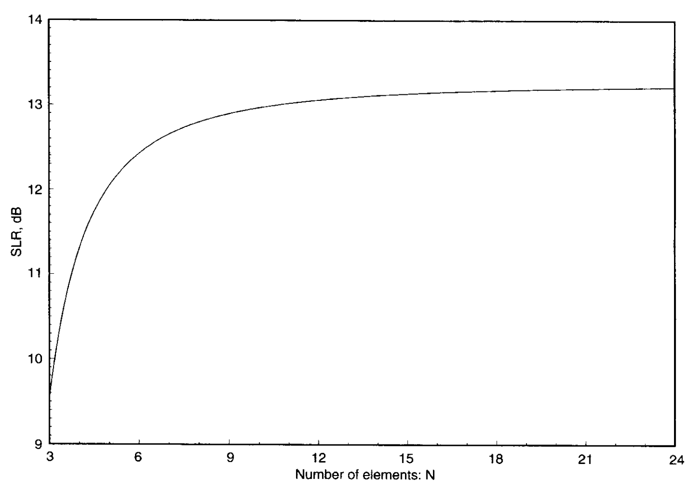

Figure A-3: Sidelobe Ratio vs. Number of Elements

Figure A-3 shows the SLR versus number of elements. In this figure, it is clearly seen that the arrays of less than 8 elements are shown to experience a significant sidelobe ratio degradation.

Grating Lobes

Large element spacings produce additional unwanted main beams, which are called grating lobes. According to [23], this is because the larger spacing allows the waves from each element to add in phase at the grating lobe (gl) angle as well as the main beam angle. The equation for grating lobes is determined by:

$$\frac{d}{\lambda} = \frac{n}{\sin\theta_0 - \sin\theta_{gl}} \qquad \text{(a-8)}$$

The onset of grating lobes versus scan angle is shown in Figure A-4. The common rule that half-wave spacing precludes grating lobes is not quite accurate, as part of the grating lobe may be visible for extreme scan angles.

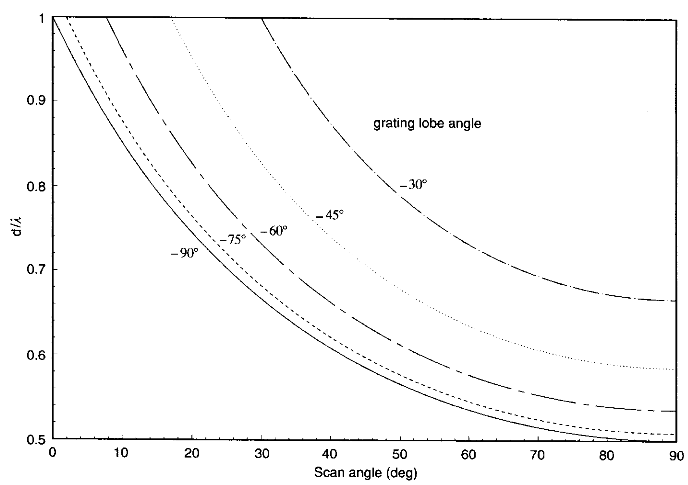

Figure A-4: Grating Lobe Appearance vs. Element Spacing and Scan

Bandwidth

According to [23], bandwidth of an array is affected by many factors, including change of element input impedances with frequency, change of array spacing in wavelengths that may allow grating lobes, change in element beamwidth, etc. Fractional bandwidth can be derived from:

$$BW = \frac{f_2 - f_1}{f_0} = \frac{(\sin\theta_2 - \sin\theta_1)\sin\theta_0}{\sin\theta_1 \sin\theta_2} \qquad \text{(a-9)}$$

where, f_1 = lower frequency,

f_2 = upper frequency.

For large arrays, this equation yields to:

$$BW \approx \frac{\theta_{3dB}}{\sin\theta_0} \approx \frac{0.866\lambda}{L\sin\theta_0} \qquad \text{(a-10)}$$

For a uniform array, this can be simplified as:

$$BW \approx \frac{\lambda}{L\sin\theta_0} \qquad \text{(a-11)}$$

Beam angle θ is simply related to scan angle θ_0 as shown in Figure A-5.

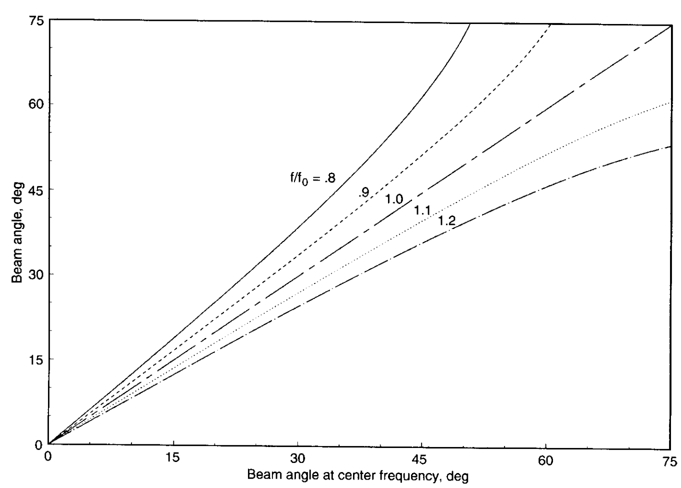

Figure A-5: Beam Angle Shift With Frequency

Directivity

According to [23], the directivity of a linear array is the integrated power radiation pattern over a sphere divided by the power density at the angle of interest. Since conduction losses of the arrays are usually much less than radiation resistances, the gain and directivity are essentially equal, except for impedance mismatch effects. Directivity, D, is given by:

$$D = \frac{4\pi |F|^2}{\int_0^{2\pi} \int_{-\pi/2}^{\pi/2} |AF(\theta,\phi)|^2 (\cos\theta) d\theta d\phi} \qquad \text{(a-12)}$$

For a uniform broadside array, the Array Factor is rationally symmetric due to isotropic elements, which will lead to a simplification as:

$$D = \frac{N^2}{\int_0^{\pi/2} \frac{\sin^2\{(1/2)Nkdu\}}{\sin^2\{(1/2)kdu\}} \cos\theta d\theta} \qquad \text{(a-13)}$$

This can be integrated with the help of an expansion Whittaker and Watson [23], and the resulting directivity becomes as:

$$D = \frac{N^2}{N + 2\sum_{n=1}^{N-1} (N-n) \frac{\sin(nkd)}{nkd}} \qquad \text{(a-14)}$$

Figure A-6 shows array directivity versus spacing for various arrays from 2 to 24 elements. It can be noted that the directivity drops abruptly at the appearance of the first grating lobe, to about the value obtained at half-wave spacing.

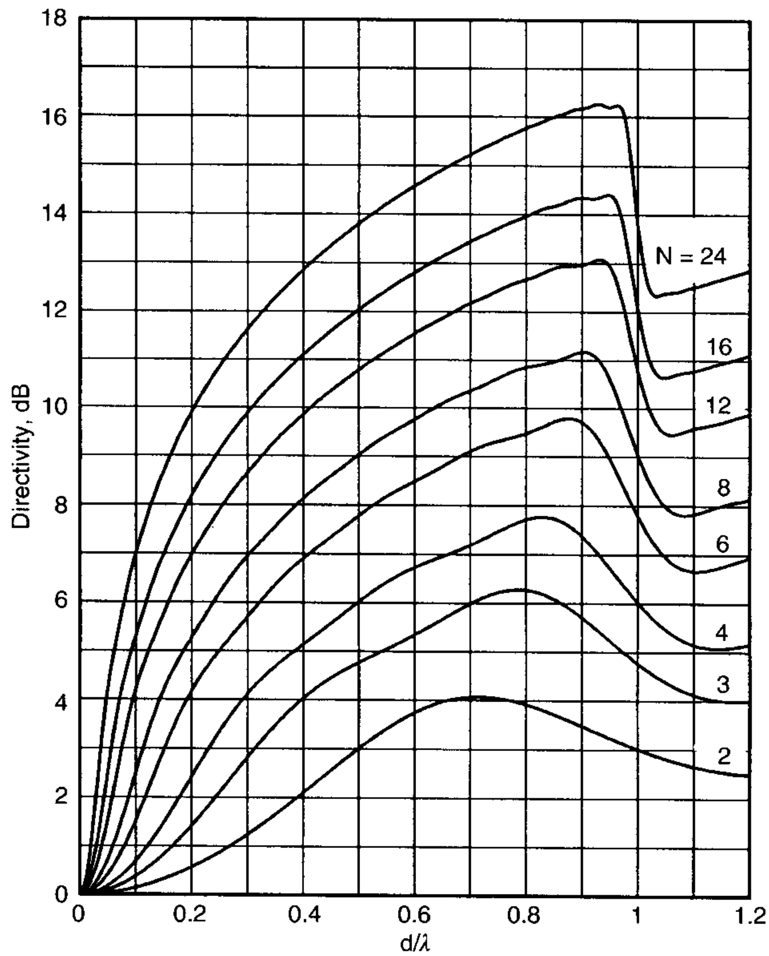

Figure A-6: Directivity vs. Array of Isotropic Elements

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14. ABSTRACT

Passive Coherent Location (PCL) systems use a special form of a radar receiver that exploits the ambient radiation in the environment to detect and track targets. Typical transmissions of opportunity that might be exploited include television and FM radiobroadcasts. PCL implies the use of a non-radar electromagnetic sources of illumination, such as commercial radio or television broadcasts, also referred as transmitters of opportunity. The use of such illumination sources means that the receiver needs to process waveforms that are not designed for radar purposes. As a consequence, the receivers for PCL systems must be much more customized than traditional receivers, in order to obtain the most appropriate and best signal.

Since antennas are the *eyes* of the receivers, processing of an incoming signal starts with the antennas. Yet, because PCL system is non-traditional, there has not been much work done in the evaluation of the antennas, even though PCL systems have some demanding constraints on the antenna system. During this research various array antenna designs will be studied by their radiation patterns, gain factors, input impedances, power efficiencies, and other features by simulating these arrays in the computer environment. The goal is to show the better performance of the array antennas compared to traditional Yagi-Uda antennas that are currently used for PCL systems.

15. SUBJECT TERMS

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